DIGITAL COMPUTATION OF CONTINUOUS CURRENT CARRYING CAPACITY OF CABLES

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By

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CERTIFICATE

It is certified that the work contained in this thesis entitled, "**DIGITAL COMPUTATION OF CONTINUOUS CURRENT CAPACITY OF CABLES**' has been carried out by **ANAND KISHOR** under my supervision and the same has not been submitted elsewhere for the award of a degree.

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Dedicated to My Parents

ABSTRACT

To achieve maximum economy in cost and subsequently in operation of cables, an important aspect is the selection of the optimum size of conductor. Several factors are involved in this consideration. While the continuous current carrying capacity is paramount, other factors such as voltage drop, cost of losses and ability to carry short circuit currents must not be neglected. The current rating is dependent on the way the heat is transmitted to the cable surface and then dissipated to the surroundings. A maximum conductor temperature is fixed which is commonly the limiting temperature for the insulation material. This ensures a reasonable life for the cable. Then by choosing a base ambient temperature for the surroundings, a permissible temperature rise is obtained from which the maximum cable rating can be computed for the particular environment.

Various factors and aspects dealing with different possible combinations of circumstances need to be considered. For example losses in metal sheaths and armour, eddy current losses (for a.c. cables), thermal resistance of different parts of cables, different conditions of installations, heat dissipating properties of the cable etc. Taking all these factors into considertion, the calculation really turns out to be enormous, using more than a hundred different formulae and more than a hundred and fifty different variables! An algorithm for the computation of continuous current rating has, therefore, been developed and the same has been implemented as computer program. Care should be taken in applying the appropriate rating factors to cater for the actual installation conditions and mode of operation.

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ANAND KISHOR

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SYMBOLS AND NOTATIONS

The symbols used in this work and the quantities which they represent are given as following:

A	Cross-sectional area (mm^2)
A_s	Cross-sectional area of sheath/concentric conductor (mm^2)
A_a	Cross-sectional area of armour (mm^2)
B	Coefficient used in clause 9.2.1
C	Capacitance per phase of the cable ($\mu F/km$)
D_d	Internal diameter of duct (mm)
D_e	External diameter of cable, or equivalent diameter of a group of cores in pipe-type cable (mm)
D_e^*	$D_e \times 10^{-2}$
D_o	Outside diameter of duct (mm)
D_s	External diameter of metal sheath (mm)
F	Coefficient defined in Clause 6.2.4
G_1	Geometric factor for belted cables (Clause No. 8.1.1)
G_b	Thermal resistance between sheath and armour ($^\circ C$ cm/W)
G_e	Thermal resistance of surrounding medium (ratio of cable surface temperature rise above ambient to the losses per unit length) ($^\circ C$ cm/W)
G_e^*	External thermal resistance of free air, adjusted for sold radiations. ($^\circ C$ cm/W)
G_e'	External thermal resistance between cable and duct (or pipe) ($^\circ C$ cm/W)
G_e''	Thermal resistance of duct itself (or pipe ($^\circ C$ cm/W)
G_e'''	External thermal resistance of medium surrounding the duct (or pipe) ($^\circ C$ cm/W)
G_i	Thermal resistance of insulation per core between conductor and sheath ($^\circ C$ cm/W)

G_s	Thermal resistance of external servings (°C cm/W)
G_{si}	Simons correction factor as used in clause 8.1.2.1
$\bar{G}_1$	Geometric factor for SL and SA type cables
H	Intensity of solar radiation (clause 9.2.2) (W/km)
I	Permissible continuous current carrying capacity of each conductor (rms value)
a	Axial distance between conductors (mm)
b	Shortest minor length in a cross-bonded electrical section having unequal minor lengths
c	Distance between the axes of conductors and the axis of the cable (mm)
d_a	Mean diameter of armour (mm)
d_{bs}	Diameter below serving/outer sheathing (mm)
d_c	external diameter of conductor including semiconducting layers (if any) (mm)
d_{cm}	Minor diameter of an oval conductor (mm)
d_{cM}	Major diameter of an oval conductor (mm)
d_1	External diameter of the insulated core (mm)
d_n	distance between axis of the cable under consideration and axis of nth cable (mm)
$d_{n'}$	Distance between axis of the cable under consideration and axis of reflection of nth cable (mm)
d_s	Mean diameter of sheath/concentric conductor (mm)
g_s	Coefficient used in clause 6.2.3
f	System frequency
g	Coefficient used in clause 6.2.3
h	Heat dissipation coefficient $(W/m^2(C)^{5/4})$
k	Factor used in the calculation of hysteresis losses in armour or reinforcement (Clause 7.3.2)

k'_a	Factor to account for direct solar radiation for calculating G_e for cable in free air (°C)
k_l	Numerical factor to take in account of actual length of concentric conductor
k_{la}	Numerical factor to taken in account of actual length of armour
k_p	Numerical used in calculating x_p (proximity effect)
k_s	Numerical factor used in calculating x_s (skin effect)
l	Length of a cable section (m)
l_n	Natural logarithm (ie. logarithm to base a)
m	$= \frac{\omega}{R_s} 10^{-4}$ used in clause 6.2.3
p_e	The part of the perimeter of the cable through which is effective for heat dissipation (mm)
p, q	Coefficients used in Clause 6.2.2
p', q', r'	Coefficients used in Clause 9.3
r	Radius of circular conductor including semiconducting layers (if any) (mm)
r_1	Circumscribing radius of two or three sector shaped conductors (mm)
S_1	Axial separation of two adjacent cables in a horizontal group of three, not touching (mm)
S_2	Axial separation of cables (Clause 7.2) (mm)
t'_b	Thickness of bedding (mm)
t_s	Thickness of serving (mm)
t_i	Thickness of core insulation, including screening layer (if any) (mm)
$t_{b'}$	Thickness of bedding (inner sheathing) (mm)
t_s	Thickness of sheath (mm)

t_{sc}	Thickness of metallic screen/concentric conductor (mm)
u	$= \frac{2L}{D_e} =$ in sub-clause 9.1
u_1	$= \frac{L_G}{r_b} =$ in sub-clause 9.3
x, y	Coefficients used in clause 8.1.2.1
x_1, y_1	Coefficient used in clause 8.1.2.2
x_2, y_2	Coefficients used in clause 8.1.2.3
x_p	Argument of a Bessel function used to calculate proximity effect
x_s	Argument of Bessel function used to calculate skin effect
y_p	Proximity effect factor
y_s	Skin effect factor
α_{20}	Temperature coefficient of electrical resistivity at 20°C per °C
k	Screening factor for screened cables
k_A	Coefficient used in Clause 9.2.1
L	Depth of laying, to cable axis or centre of trefoil (mm)
L_G	Distance from the soil surface to the centre of a duct block (mm)
M	Mie formula as defined in clauses 8.1.2.1
M, N	Coefficients defined in Clause 6.2.4
N_1	Number of loaded cables in a duct bank (Clause 9.7.3)
P, Q	Coefficients defined in Clause 6.2.2 (ohm/km)
R	Inside radius of lead sheath/ armour (when cables do not have common sheath) (mm)

R_{ac} Alternating current resistance of conductor at its maximum operating temperature (ohm/km)

R_a Resistance of armour at operating temperature (ohm/km)

R_s Resistance of sheath at operating temperature (ohm/km)

R_{dc} dc resistance of conductor at maximum operating temperature θ_i °C (ohm/km)

R_o dc resistance of conductor at 20°C (ohm/km)

S_1 Sector correction factor to thermal resistance of circular conductor cables

S_2 Screen correction factor to thermal resistance of circular conductor belted type cable

U_o Voltage between conductor and screen or sheath (operating voltage) (V)

W_d Dielectric losses per unit length per phase (W/cm)

W_n Losses dissipated by cable n (W/cm)

W_{TOT} Total power dissipated in the trough per unit length (W/km)

X Indicative reactance of sheath/concentric conductor (two core cables and three core cables in trefoil) (ohm/km)

X_1 Inductive reactance of sheath/concentric conductor (cables in flat formation) (ohm/km)

X_m Mutual reactance between the sheath of one cable and the conductors of the other two when cables are in flat formation (ohm/km)

Y Coefficient used in Section 9.8

Z Coefficient used in Section 9.2.1

α is ratio of diameter of equitent circular conductor and diameter of circular core

α_a Temperature coefficient of electrical resistivity of armour material at 20°C per °C

α_s Temperature coefficient of electrical resistivity of sheath material at 20°C per °C

α_i, β	Coefficients used in Clause 8.1.2.1
β	Coefficient used in Clause 6.2.3
	Angular time delay (clause 7.2)
Δ_1, Δ_2	Coefficient used in Clause 6.2.3
δ	Equivalent thickness of armour or reinforcement (mm)
δ_1	Thickness of metallic screens on screened type cable (mm)
$\tan\delta$	Loss factor of insulation
ϵ_r	Relative permittivity of insulation (dielectric)
θ_c	Maximum permissible operating temperature of conductor ($^\circ$C)
θ_s	Sheath/concentric conductor temperature ($^\circ$C)
θ_a	Armour temperature ($^\circ$C)
$\Delta\theta_c$	Permissible temperature rise of conductor above the ambient ($^\circ$C)
$\Delta\theta_d$	Factor to account for dielectric loss for calculating G_e ($^\circ$C)
$\Delta\theta_{so}$	Cable surface temperature above ambient when cable protected from solar radiations ($^\circ$C)
$\Delta\theta'_{sa}$	Cable surface temperature rise above ambient when cable is exposed to solar radiations ($^\circ$C)
$\Delta\theta_{duct}$	Difference between the mean temperature of air in a duct and ambient temperature ($^\circ$C)
$\Delta\theta_n$	Cable surface temperature rise caused by nth cable ($^\circ$C)
$\Delta\theta_s$	Difference between the surface temperature of a cable in air and ambient temperature ($^\circ$C)
$\Delta\theta_{tr}$	Temperature rise of the air in a cable trough ($^\circ$C)
λ_o	Coefficient used in Clause 6.2.3

λ_1, λ_2 — Ratio of the total losses in metallic sheaths and armour respectively to the total conductor losses, (or losses in one sheath or armour to the losses in one conductor)

λ_1' — Ratio of the losses in one sheath caused by circulating currents in the sheath to the losses in one conductor

λ_1'' — Ratio of the losses in one sheath caused by eddy currents to the losses in one conductor

μ — Relative magnetic permeability of armour material

ρ_a — Electrical resistivity of armour material at 20°C (ohm/mm^2/m)

ρ_e — Thermal resistivity of earth surrounding a duct bank/ cable (°C cm/W)

ρ_c — Thermal resistivity of concrete used for a duct bank (°C cm/W)

ρ_i — Thermal resistivity of insulating material (°C cm/W)

ρ_{sc} — Thermal resistivity of metallic screens on multicore cables (°C cm/W)

ρ_{SC} — Thermal resistivity of screen material (°C cm/W)

ρ_b — Thermal resistivity of bedding (inner sheathing) material (°C cm/W)

ρ_{as} — Thermal resistivity of outer serving material (°C cm/W)

ρ_s — Electrical resistivity of sheath material at 20°C (ohm/mm^2/m)

ρ_{ed} — Thermal resistivity of material (ohm/mm^2/m)

σ — Absorption coefficient of solar radiation for the cable surface

ϕ_d — Factor to account for dielectric loss for calculating G_c for cables in free (°C)

ϕ_s — Factor to account for direct solar radiation for calculating G_e for cables in free air (°C)

ω — Angular frequency of System (2) (1/s)

CHAPTER 1
INTRODUCTION

There is a growing appreciation on the part of cable users for the selection of appropriate cable sizes if the greatest possible economy is to be achieved in power cable installations.

When heat is applied to any body at a uniform rate, an increase in temperature results, the initial rate of increase being very rapid (Fig. 1). Immediately the body temperature exceeds the ambient temperataure and a heat dissipation process begins. The magnitude of this heat loss is proportional to the temperature difference between the body and the ambient temperature (Newton's Law of Cooling). Therefore, as the temperature of the body increases, the rate of heat loss becomes larger, with a diminishing of the rate of temperature rise. Finally a stage is reached when the rate of heat generated and dissipated becomes constant. This temperature is known as the continuous operating temperature and its magnitude will depend upon the nature of the path through which the heat must dissipate, viz. the thermal resistance.

Four main factors decide the safe continuous current a cable can carry:

1. The maximum permissible temperature at which its components may be operated with a reasonable factor of safety.
2. The heat-dissipating properties of the cable.
3. The installation conditions and the ambient conditions.
4. Voltage drop (L.V. cables).

The current carried by a conductor raises its temperature until equilibrium is established and the heat generated is equal to the heat dissipated through the insulation, metal sheath, cable servings, and finally into the surrounding earth or air, as shown by Fig 2. which illustrates the mechanism of heat flow for the case of a three-phase belted-type cable.

The heat flow within a cable is reasonably radial but externally it is not so and allowance must be made for the method of installation. Fig 3 shows the pattern of heat flow for three single-core cables. It illustrates the importance of making allowance for the depth of burial and could be extended to show the effects of other cables in close proximity.

Under thermal steady state conditions the difference between the conductor temperature and the external ground or ambient temperature is related to the total heat losses and the law of heat flow which is very similar to Ohm's law. Heat flow corresponds to current, temperature difference to voltage difference and the total thermal resistance in the cable and surroundings to electrical resistance. From this basis the heat losses are often referred to as ohmic losses and using this analogy it is possible to construct a circuit diagram as illustrated in Fig. 4. This shows how the heat input at several positions has to flow through a number of layers of different thermal resistances. By measuring values of different parameters for the materials, rating calculations can then be made.

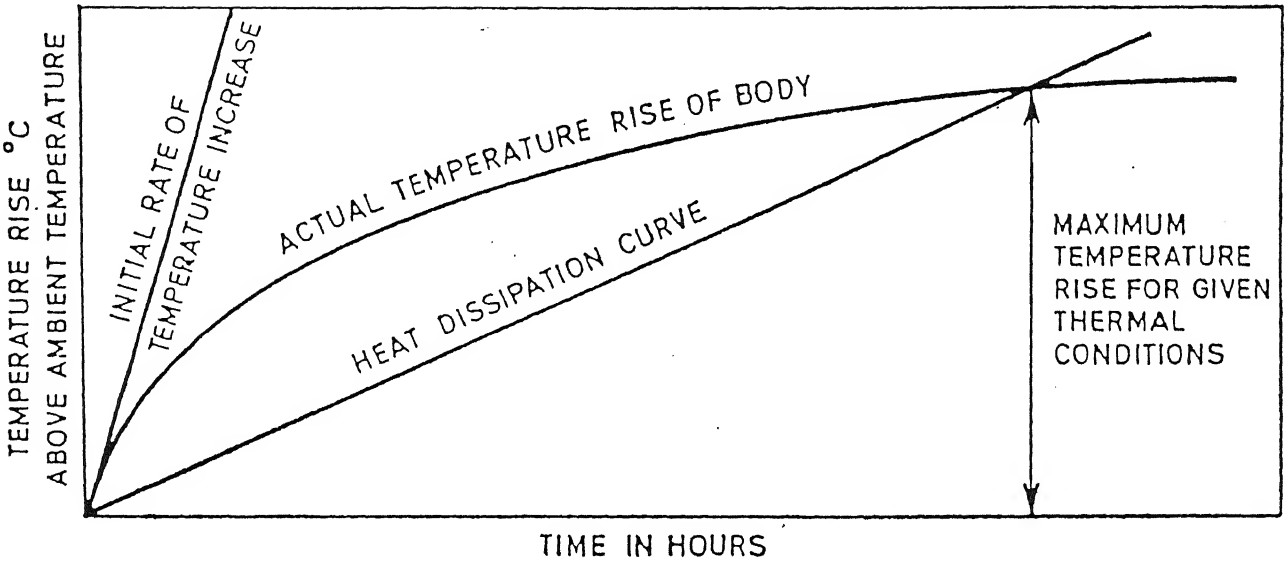

Fig. 1.

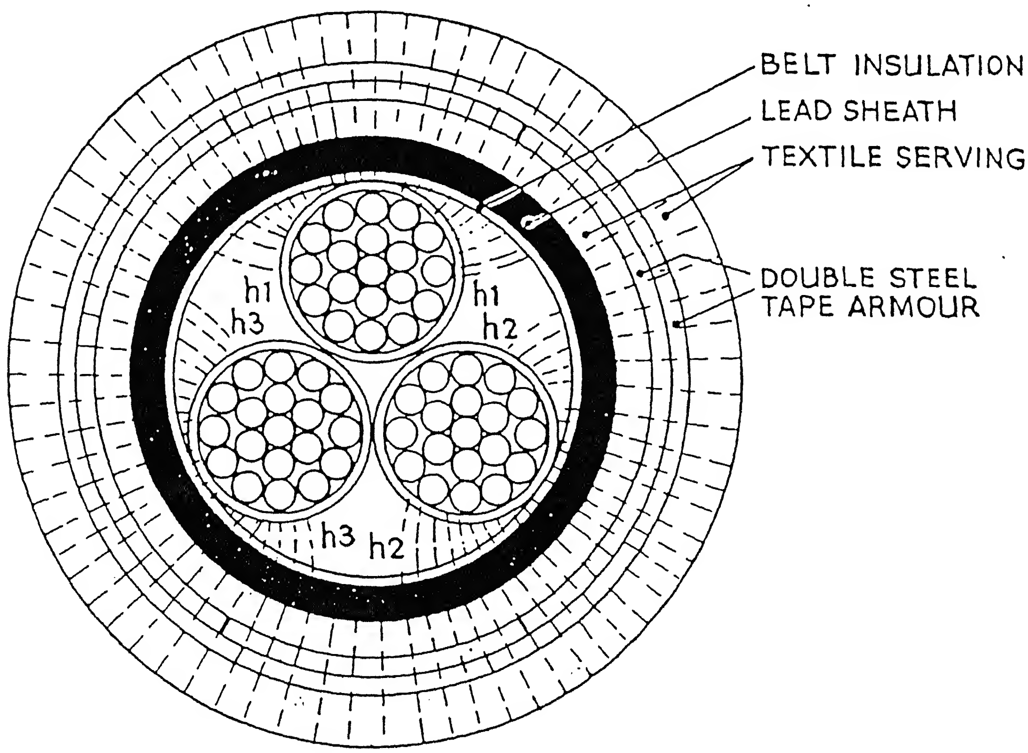

Fig 2. Paths of heat flow in a three-core belted-type cable.

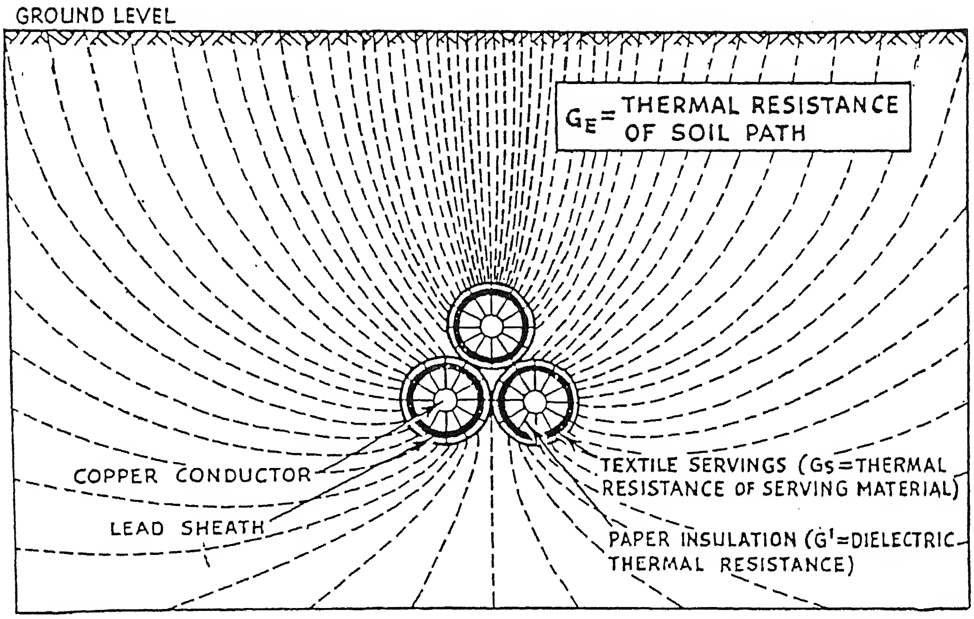

Fig. 3 Heat flow from a circuit of single-core cables installed in trefoil

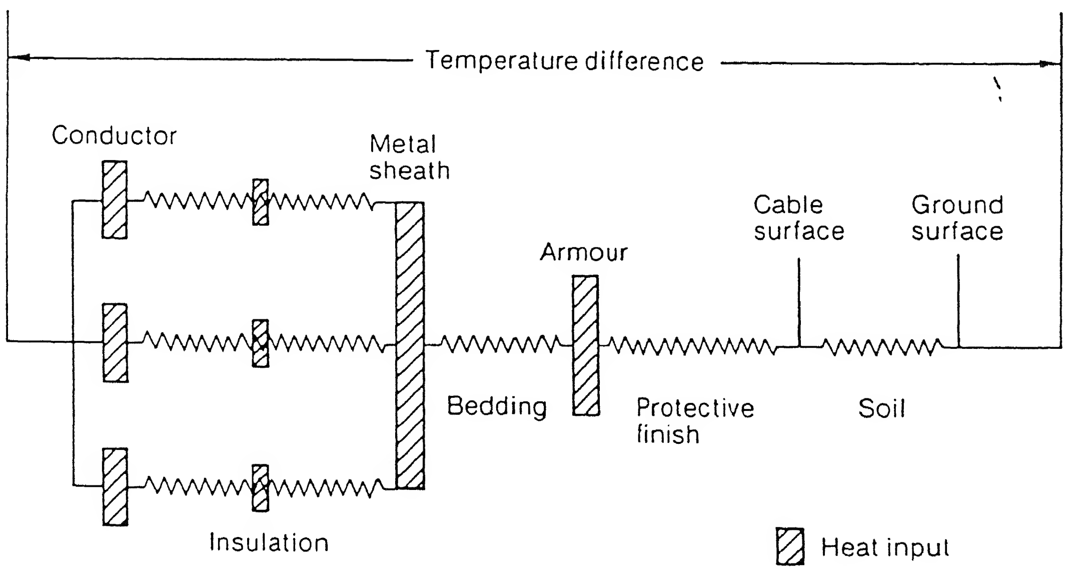

Fig. 4 Circuit diagram to represent heat generated in a 3-core metal sheathed cable

CHAPTER 2

PRACTICAL CONSIDERATIONS

The current carrying capacity of a power cable is limited by the permissible maximum temperature of the insulation which is also the maximum temperature of the cable conductor. The maximum permissible working temperature as given by IS:3961 (Part I, II, III, IV and V) - 1968 for different types of insulation are given in Table 1.

The temperature rise is a function of thermal constants of the cable, the surrounding medium and of the way in which it is laid and loaded that is the loading versus time characteristics. However, since current carrying capacities are to be computed for constant loading condition, the latter is of less importance.

In computing the conductor temperature rise and current carrying capacity of cables, the total thermal resistance of the cable and the surrounding medium must be known that is the internal thermal resistance of the cable and the external thermal resistance of the surrounding medium.

Table I

Type of Insulation	Maximum Conductor Temperature in $^{\circ}C$
Poly Venyl Chloride	70
Poly Ethylene	70
XLPE	90
Rubber	
EPR	90
Natural Rubber	60
Butyl Rubber	90
Silicon Rubber	150
Paper (c.f. IS:3961-1968 for different types)	65-85

CHAPTER 3

BASIC FORMULAE FOR THE CALCULATION OF CURRENT CARRYING CAPACITY OF CABLES

In a cable carrying current there are three sources of heat, namely:

(a) I^2R loss in the conductors

(b) Dielectric losses, and

(c) Sheath/concentric conductor losses

The current carrying capacity is calculated on the principles of heat flow in the steady state. The formula which is applicable to all types of cables conforming to IS as given by IS:3961 (parts I, II, III, IV and V) - 1968 for different types of insulation given in Table I, applicable for calculating current capacities is as under:

$$I = \sqrt{\frac{\left\{\Delta\theta_c - W_d\left[\frac{1}{2}G_i + n\left\{G_b + G_s + G_e\right\}\right]\right\} \times 10^5}{R_{ac}G_i + nR_{ac}(1+\lambda_1)G_b + nR_{ac}(1+\lambda_1+\lambda_2)(G_s+G_e)}}\ \mathrm{A} \quad (1)$$

Where

R_{ac} = Alternating current resistance per unit length of the conductor at maximum operating temperature ohm/km.

$\Delta\theta_c$ = Conductor temperature rise, in °C, above ambient

W_d = Dielectric loss in watts per unit length of the cable W/cm

G_i = Thermal insulation resistance per unit length of insulation in °C cm/W.

G_b = Thermal resistance per unit length of bedding between

sheath and armour. In case of PVC cable G_b is thermal resistance per unit length of inner sheath. If unarmoured G_b = 0.

G_s = Thermal resistance per unit length of external serving over armour. In case of PVC cables G_s is the thermal resistance per unit length of outermost covering.

G_e = Thermal resistance per unit length between the cable surface and surrounding medium

λ_1 = Ratio of losses in the metal sheath/concentric conductor to total loss in all conductors

λ_2 = Ratio of losses in the armouring to total losses in all conductors

n = Number of equally loaded conductors in cable

It should be noted that dielectric losses W_d depend upon the type of insulation provided in a cable. Table II shows the voltage rating of cables for which W_d is negligible and therefore can be taken as equal to zero.

Table II

Voltage Rating upto which the dielectric loss can be considered negligible

S.No.	Type of Insulation	Voltage Rating
1.	Paper	22 kV
2.	PVC	3.3 kV
3.	PE	110 kV
4.	XLPE	33 kV
5.	Rubber	22 kV

CHAPTER 4

LOSSES IN THE CABLE

4.1 AC RESISTANCE OF THE CONDUCTOR

The ac resistance per unit length of a conductor is given by

$$R_{ac} = R_{dc} \left\{1 + y_s + y_p\right\} \text{ ohm/km} \tag{2}$$

where

R_{dc} dc resistance/unit length at maximum permissible temperature in ohm/km

y_s skin effect

y_p proximity effect factor

The dc resistance R_{dc} can be computed from the formula

$$R_{dc} = R_o \left[1 + \alpha_{20} \left\{\theta_c - 20\right\}\right] \text{ ohm/km} \tag{3}$$

where

R_o dc resistance/unit length at 20°C

α_{20} temperature coefficient of conductor resistivity per °C at 20°C

θ_c maximum permissible continuous temperature in °C (Table 1).

The value of R_o at 20°C for copper and aluminium conductors are available in IS:2982-1965 and 1753-1967 or IS:8130-1984 respectively while α_{20} corresponding to the two conductors is 0.00393 and 0.00403 per °C.

4.2 SKIN EFFECT FACTOR

Due to the alternating magnetic field produced when a conductor is carrying alternating current, the current is not uniformly distributed throughout its cross section. Consequently, there is an increase in I^2R loss, the net effect of

which is similar to an increase in ohmic resistance of the conductor. The skin effect is a function of frequency, conductor cross-section area and permeability. The skin effect factor, which estimates the increase in resistance can be written as

$y_s = F(x_s)$

where

$$x_s = \sqrt{\frac{8 p f k_s}{R_{dc}} \times 10^{-4}} \qquad (4)$$

f_s frequency in cycles per second

k_s a numerical factor which is unit for all conductors except for round segmental and hollow

For $x_s < 2.8$, the factor y_s can be estimated as:

$$y_s = \frac{x_s^4}{192 + 0.8\, x_s^4} \qquad (5)$$

Calculations have shown that for f = 50 Hz and for all values of R_{dc} of aluminium/ copper conductors conforming to IS:8130-1984, the values of x_s is less than 2.8. Hence the formula (5) is applicable for all practical cases.

4.3 PROXIMITY EFFECT FACTOR y_p

In a cable, due to the conductors being placed close together the effect of the field due to the return conductor cannot be ignored. The effect of this field is to distort the current distribution in the conductor. This effect is again similar to an increase in resistance. Proximity effect is more predominant for large conductors, high frequencies and close proximity. In cables, the proximity effect is relatively more in three core cables than in single core cables.

The proximity factor, y_p can be written as

$$y_p = F\left[x_p\right]$$

where $$x_p = \sqrt{\frac{8\pi f k_p}{R_{dc}} \times 10^{-4}} \tag{6}$$

k_p is a numerical factor which has a value of 0.8 for stranded conductors, dried and impregnated conductors and 1.0 for unimpregnated conductors of both solid and stranded types. The above is applicable for all conductors except for hollow and segmental conductors.

The above values are experimentally determined for Cu conductors, and also recommended for Al conductors. Whether the value of k_p is affected by stranding or impregnation, is not well explained in these two references.

The proximity effect factor for various types of conductors can be computed as following:

(a) For two stranded circular conductors carrying single phase current, that is for two core cables and for two single core cables :

$$y_p = \frac{\alpha^2 G(X_p)}{1 - \alpha^2 A(X_p) - \alpha^4 B(X_p)} \tag{7}$$

(b) For three stranded circular conductors carrying three phase currents :

$$y_p = \frac{1.5\ \alpha^2 G(X_p)}{1 - \frac{5}{14}\ \alpha^2 H(X_p)} \tag{8}$$

(c) For three stranded sector shaped conductors carrying three phase currents :

$$y_p = \frac{5}{6} \times \left[\begin{array}{l} y_p \text{ for three stranded circular conductors} \\ \text{carrying three phase currents} \end{array}\right] \tag{9}$$

(d) For four stranded sector shaped conductors carrying three phase currents fourth core idle :

$$y_p = \frac{\alpha^2 G(X_p)}{1 - \frac{5}{4}\alpha^2 H(X_p)} \qquad (10)$$

where α is defined as:

$$= \frac{d_c \text{ (diameter of circular conductor or equivalent circular conduct}}{d_c + \text{Thickness of Insulation between conductor}}$$

Function $G(x_p)$

For $0 < x_p \leq 1.7$ $\qquad G(x_p) = \frac{11x_p^4}{704 + 20\ x_p^4}$

and for $1.7 < x_p < 5$

$$G(x_p) = 1.45755 - 3.01244x_p + 2.37367\ x_p^2 - 0.876292x_p^3 + 0.17342x_p^4 - 0.0176942x_p^5 + 0.000733857x_p^6$$

Function $A(x_p)$

For $0 < x_p \leq 1.7$ $\qquad A(x_p) = \frac{1}{24} + \frac{8x_p^4}{700 + 19x_p^4}$

and for $1.7 < x_p \leq 5$

$$A(x_p) = 0.572847 - 1.07138x_p + 0.772580x_p^2 - 0.222146x_p^3 + 0.0297573x_p^4 - 0.00154569x_p^5$$

Function $B(x_p)$

For $0 < x_p \leq 1.4$ $\qquad B(x_p) = 0$

For $1.4 < x_p \leq 9$

$$B(x_p) = -0.0204565 + 0.0627116x_p - 0.0582560\ x_p^2 + 0.0212377x_p^3 - 0.00359679x_p^4 + 0.000287892x_p^5 - 0.0000891109x_p^6$$

and the function of $H(x_p) = \frac{F(x_s)}{G(x_p)}$ where the function $F(x_s)$ is the skin effect factor.

CHAPTER 5
DIELECTRIC LOSS

The dielectric loss, W_d, in a cable is given by

$$W_d = \omega CU_o^2 \tan\delta \text{ Watts/ km} \qquad (11)$$

where $\omega = 2\pi f$ radians/s

C = capacitance per phase of the cable in μF/km

U_o = Voltage to earth in kV (operating voltage)

(It should be noted that in an unearthed system the voltage to be considered is the line to line voltage of the system even if the cable is screened).

$\tan\delta$ = Dielectric loss factor at power frequency, maximum permissible operating temperature and operating voltage.

5.1 CALCULATION OF CAPACITANCE

Capacitance per phase of a screened core cable is given by

$$C = \frac{\varepsilon_r}{18\ln\left(\frac{di}{dc}\right)} \ \mu\text{F/km} \qquad (12)$$

where

ε = Relative permittivity constant of the dielectric

d_i = External diameter of the insulated conductor (core) excluding screen and semi conducting layer.

d_c = Diameter of conductor including semi conducting screen, if any.

The same formula can be used for oval conductors if the geometric mean of the appropriate major and minor diameters is substituted for d_i and d_c.

In case of sector shaped conductors the same formula can be employed if dimensions of equivalent circular conductor are

taken.

For three core belted cables with paper insulation and three core plastic cables with screen or concentric conductor surrounding the laid up cores the capacitance per phase of the cable can be computed as follows:

$$C = \frac{2\pi\varepsilon_o\varepsilon_r}{\ln\sqrt{\dfrac{3a^2(r_1^2 - a^2)}{r_F^2\ (r_1^6 - C^6)}}} \qquad (13)$$

r_f radius of the conductor or inner conducting layer (if present)

r_1 radius of insulation

Although it is possible to compute the capacitance per phase of the conductor by the above formula yet it is recommended that the actual value of capacitance obtained by measurement, be used.

Concentric conductor or shield consists of copper or aluminium and may constitute of a layer of helically applied round wires or flat strips and tape around the core concentrically. The concentric conductors and shields are always placed below the outer plastic sheath. In India cables with concentric conductors were not manufactured earlier. With plastic cables, particularly XLPE, becoming popular, cables with concentric conductors are gaining popularity.

A study of the literature shows considerable variations in relative permittivity and tan δ for various types of insulants. Table III below gives the average values of permittivity and tan δ for computing the capacitance per phase and dielectric loss in cables.

Table III

Average value of Relative Permittivity ε_r and δ of various insulants

S. No.	Type of Insulation	Relative Permittivity	tan δ
1.	Impregnated paper	3.8	0.010
2.	PVC	6.0	0.100
3.	Rubber	3.8	0.010
4.	PE	2.3	0.001
5.	XLPE	2.3	0.008

CHAPTER 6

SHEATH/CONCENTRIC CONDUCTOR (SCREEN) POWER LOSS FACTOR λ_1

This is applicable only for cables used in ac system. The factor λ_1 is defined as the ratio of sheath/screen loss to the total power loss in all the conductors in the cable. The power loss in sheath/screen consists of losses caused by circulating currents λ_1' and eddy currents λ_1''. Only for cables with large segmental conductors and for multicore cables with common sheath the losses due to eddy currents in the sheath should be taken in to account.

In case of single core cables, formula for λ_1 is given for single circuit, the effect of earth return path is neglected. When cables are bonded at both ends, the losses caused by circulating currents are large as compared to losses caused by eddy currents. Hence only losses caused by circulating currents are considered, except in the case of large segmental conductors, where both the losses are essentially computed. For cross bonded installations, all the small sections can not be considered to be electrically identical, thus causing some circulating currents. However if the exact details of cross bonding is not available, it can be assumed that small section are electrically identical and losses due to eddy current need only be considered.

Hence, an electrical section is defined as a portion of the route between points at which sheaths or screens of all the cables are solidly bonded.

$$\lambda_1 = \lambda_1' + \lambda_1'' \qquad (14)$$

The electrical resistivities and temperature coefficients for metals commonly used for sheath/screen material are given in Table IV.

Table IV

Recommended values of ρ_s and α_s of sheath/screen materials

S.No.	Metal	ρ_s in ohm mm^2/m or 10^{-6} ohm m at 20°C	α_s in per °C at 20°C
1.	Conductors		
	Copper	0.017241	0.00393
	Aluminium	0.028264	0.00403
2.	Sheath/Screen/Armour		
	Lead or Lead Alloy	0.021400	0.00400
	Aluminium	0.02845	0.00403
	Steel	0.13800	0.00450

6.1 SHEATH/CONCENTRIC CONDUCTOR (SCREEN) RESISTANCE R_S:

The sheath/concentric conductor resistance R_s given by:

$$R_s = \frac{\rho_s \left[1 + \alpha_s \left\{\theta_s - 20\right\}\right] \times 10^3 \times k_1}{A_s} \text{ ohm/km} \qquad (15)$$

where

ρ_s Electrical Resistivity of the material at 20°C is ohm mm^2/m

α_s Temperature coefficient of the material at 20°C is per °C

θ_s Sheath/concentric conductor temperature in °C

A_s Cross sectional area of sheath/concentric conductor mm^2

k_1 Numerical factor to take into account the actual length

Value of k_1

For lead/Aluminium extruded sheath $- k_1 = 1.00$

For steel/Aluminium wire or strip $- k_1 = 1.10$

The computation of the sheath/concentric conductor temperature θ_s can be done by the general formula given below:

$$\theta_s = \Delta\theta_c \times \left[\frac{\text{Sum of thermal resistance upto sheath/concentric conductor starting from the surrounding medium}}{\frac{G_i}{n} + \text{Sum of thermal resistance upto sheath/ concentric conductor starting from the surrounding medium}}\right] + \theta_{am} \qquad (16)$$

Thus for a PILC cable

$$\theta_s = \Delta\theta_c \frac{(G_e + G_s + G_b)}{\frac{G_i}{n} + G_e + G_s + G_b} + \theta_{ambient} \qquad (17)$$

The sheath/concentric conductor loss factor λ_1 for different types of ac cables is determined as described below:

6.2 SHEATH/CONCENTRIC CONDUCTOR LOSS FACTOR FOR SINGLE CORE CABLES

6.2.1 Three Single Core Cables Trefoil Formation and Two Single Core Cables, Sheath/Concentric Conductor Bonded at Both Ends.

In this case eddy current losses are small and can be neglected except for the large segmental conductors. Therefore,

$$\lambda_1 = \lambda_1'$$

$$\lambda_1 = \frac{R_s}{R_{ac}} \frac{1}{1 + \left(\frac{R_s}{x}\right)^2} \qquad (18)$$

where

X = inductive reactance of sheath/concentric conductor per unit length of cable

$$X = 4\pi f.\ \ln \left(\frac{2a}{d_s}\right) 10^{-4} \text{ ohm.km} \qquad (19)$$

where a = axial distance between conductors (mm)

d_s = mean diameter of sheath/concentric conductor (mm)

6.2.2 Three single core cables in flat formation, bonded at both ends

As in the case 6.2.1, the eddy current losses can be neglected in this case too. However, the transposition of cables shall affect the circulating current losses. Assuming the middle cable equidistant from the outer cables;

a. Cables with regular transposition:

$$\lambda_1 = \frac{R_s}{R_{ac}} \frac{1}{1 + \left(\frac{R_s}{X_1}\right)^2} \qquad (20)$$

where

X_1 = Inductive reactance of sheath/concentric conductor per unit length of cable

$$X_1 = 4\pi f \ \ln \sqrt[3]{2} \left(\frac{2a}{d_s}\right) 10^{-4} \text{ ohm/km} \qquad (21)$$

b. Cables without transposition:

The outer cable, carrying the lagging phase shall have the maximum sheath losses. The rating for cables should be based on extreme conditions, therefore the sheath loss factor for this case should be considered, hence the factor λ_1 is given by the following formula:

$$\lambda_1 = \frac{R_s}{R_{ac}} \left[\frac{\frac{3}{4} P^2}{R_s^2 + P^2} + \frac{\frac{1}{4} Q^2}{R_s^2+Q^2} + \frac{2R_s P\ Q\ X_m}{\sqrt{3}\ (R_s^2+P^2)(R_s^2+Q^2)}\right] \qquad (22)$$

where

$P \qquad X + X_m$

Q $\quad X - \frac{X_m}{3}$

X_m Mutual reactance between the sheath of an outer cable and the conductors of other two cables per unit length of cable.

$X_m = 4\pi f.\ \ln(2).10^{-4}$ ohm/km

6.2.3 Single core cables with sheath/concentric conductor bonded at a single point or cross bonded.

As there will be no circulating currents in these cases, only eddy current losses are needed to be considered. Therefore, $\lambda_1 = \lambda_1''$.

$$\lambda_1 = \frac{R_s}{R_{ac}}\left[g_s\ \lambda_o(1 + \Delta_1 + \Delta_2) + \frac{(\beta_1 t_s)^4}{12.10^{12}}\right] \qquad (23)$$

where

$$g_s = 1 + \left(\frac{t_s}{D_s}\right)^{1.74}\left(\beta_1 D_s 10^{-3} - 1.6\right)$$

$$\beta_1 = \sqrt{\frac{4\pi\omega}{10\rho_s}}$$

ρ_s = electrical resistivity of sheath/concentric conductor material at working temperature in ohm mm^2/m (Table IV)

D_s = External diameter of cable sheath/concentric conductor in mm

t_s = Thickness of sheath/concentric conductor in mm

Note : 1. For lead sheath cables g_s can be taken as unity and the second term in formula (23) can be neglected. Hence this formula effectively reduces to

$$\lambda_1 = \frac{R_s}{R_{ac}}\left[g_s\ \lambda_o(1 + \Delta_1 + \Delta_2)\right] \qquad (24)$$

2. For Aluminium sheathed/concentric conductor cables upto sheath diameter of 70 mm the formula given above in Note

1 can be used. However, for sheath diameter above 70 mm and for unusually thick sheaths the formula (23) should be used.

Formulae for λ_o, Δ_1, Δ_2 are given below

(i) For three single core cables in trefoil formation:

$$\lambda_o = 3 \left[\frac{m^2}{(1+m^2)}\right]\left[\frac{d_s}{2a}\right]^2$$

$$\Delta_1 = \left[1.14m^{2.45} + 0.33\right]\left[\frac{d_s}{2a}\right]^{(0.92m+1.66)}$$

$$\Delta_2 = 0$$

where $m = \frac{\omega}{R_s} 10^{-4}$

$\omega = 2\pi f$

(ii) For three single core cables in flat formation

The value of λ_o, which determines the effective value of λ_1 depends upon the position of the cable. As given in the value of λ_o works out to be maximum for the middle cable. Hence the value for the middle cable is recommended for computation in this case.

$$\lambda_o = 6 \left[\frac{m^2}{(1+m^2)}\right]\left[\frac{d_s}{2a}\right]^2$$

$$\Delta_1 = \left[0.86m^{3.08}\right]\left[\frac{d_s}{2a}\right]^{(1.4m+0.7)}$$

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$$\Delta_2 = 0$$

6.3 SHEATH/CONCENTRIC CONDUCTOR LOSS FACTOR λ_1 FOR MULTICORE CABLES

6.3.1 Three Core Unarmoured Cables With Common Sheath

The power loss in the sheath/concentric conductor in this case will be contribute only by the eddy currents as the losses due to circulating currents will be negligible. The loss factor

is calculated as following:

6.3.1.1 For sector shaped conductors

$$\lambda_1 = \lambda_1'' = 0.94 \frac{R_s}{R_{ac}} \left(\frac{d_s - t_s - 2t_b}{d_s}\right) \left[\frac{1}{1+\left(\frac{R_s}{\omega} 10^4\right)^2}\right] \quad (26)$$

where d_s = mean diameter of sheath mm

t_s = thickness of sheath mm

t_b = thickness of belt insulation (if any) mm

6.3.1.2 For circular and oval shaped conductors when R_s is less than or equal to 0.1 ohm/km

$$\lambda_1 = \lambda_1'' = \frac{3 R_s}{R_{ac}} \left[\left(\frac{2c}{d_s}\right)^2 \frac{1}{1+\left(\frac{R_s}{\omega} 10^4\right)^2} + \left(\frac{2C}{d_s}\right)^4 \frac{1}{1+4\left(\frac{R_s}{\omega} 10^4\right)^2}\right] \quad (27)$$

and when R_s is greater than 0.1 ohm/km

$$\lambda_1 = \lambda_1'' = \frac{3.2\omega^2}{R_{ac} R_s} \left(\frac{2c}{d_s}\right) . \ 10^{-8} \quad (28)$$

where c = distance between axis of one conductor and the axis of cable.

c = 1.16xCore (insulated conductor)diameter

$= 1.16 \ (d_c + 2t_i)$ mm

$= 1.16 \ d_i$

6.3.2 Two Core Unarmoured Cables with Common Sheath

The circulating current losses will be negligible as in 6.3.1. Only the eddy currents will contribute to power loss in the sheath.

6.3.2.1 For sector shaped conductors

$$\lambda_1 = \lambda_1'' = \frac{10.8\omega^2 \ 10^{-10}}{R_{ac} R_s} \left(\frac{1.48 \ r_i + 2t_i}{d_s}\right)^2 \times$$

$$\left[12.2 + \left(\frac{1.48\ r_i + 2t_i}{d_s}\right)^2\right] \tag{29}$$

where r_1 = radius of the circle circumscribing the two shaped conductors

$$r_1 = \left(\frac{d_s - t_s - 2t_b - 2t_i}{2}\right) \text{ mm}$$

t_i = Thickness of insulation on the conductor mm (Core insulation)

6.3.2.2 For circular and oval shaped conductors

$$\lambda_1 = \lambda_1'' = \frac{16\ \omega^2\ 10^{-8}}{R_{ac} R_s} \left(\frac{c}{d_s}\right)^2 \left[1 + \left(\frac{c}{d_s}\right)^2\right] \tag{30}$$

6.3.3 Three and two core cables with common sheath and steel tape armour

The steel tape armour increases the eddy current losses in the sheath. The value of λ_1 calculated in 6.3.1 and 6.3.2 are suggested to be increased by the factor F_1 for steel tape armoured cables. This factor is calculated as following:

$$F_1 = \left[1 + \left(\frac{d_s}{d_a}\right)^2 \frac{1}{1 + \frac{d_a}{\mu\delta}}\right]^2 \tag{31}$$

where d_a = mean diameter of armour mm

μ = relative permeability of steel tape (usually taken as 300)

δ = equivalent thickness of armour

$= \frac{A_a}{d_a \pi}$ mm

A_a = Cross-sectional area of armour mm^2

Note : For the wire and strip armoured cables, the effect of

armour induced voltages on sheath power loss can be neglected. Such cases can be dealt as unarmoured cables.

6.3.4 Cables with separate lead sheaths and armoured

For three core SL and HSL type of cables the eddy current losses can be neglected. Hence the loss factor is given by

$$\lambda_1 = \lambda_1'' = \frac{R_s}{R_{ac}} \left[\frac{1.7}{1 + \left(\frac{R_s}{X} \right)^2} \right] \tag{32}$$

CHAPTER 7
ARMOUR LOSS FACTOR λ_2

The armour loss factor λ_2 is defined as the ratio of losses in the armour (also known as reinforcement) to the total power loss in all the conductors in the cable.

The energy loss in the magnetic armour reinforcing the power cable arise mainly due to eddy currents induced in the armour by electro-magnetic field created due to alternating currents in the conductors, hence it is applicable for ac cables only. In magnetic armour materials, there will also be significant hysteresis losses due to the same electromagnetic field. The total armour loss comprises of the hysteresis and eddy current losses. Therefore

$\lambda_2 = \lambda_2' + \lambda_2''$

where λ_2' takes care of the loss due to hysteresis and λ_2'' of the eddy current losses.

7.1 ARMOUR RESISTANCE R_a

The armour resistance R_a is given by

$$R_a = \frac{\rho_a\left[1 + \alpha_a\left(\theta_a - 20\right)\right]}{A_a} \times 10^3 \times k_{1a} \text{ ohm/km} \qquad (33)$$

where

ρ_a Electrical Resistivity of armour at 20°C in ohm mm^2/m (Table IV)

α_a Temperature coefficient of armour material per °C at 20°C (Table IV)

θ_a Armour temperature in °C

A_a Cross sectional area of armour in mm^2

k_{1a} Numerical factor to take into account the actual length of armour per km length of the cable

The armour temperature θ_a can be determined in the same way as in 6.1 and it is given by

$$\alpha_a = \Delta\theta_c \frac{\left(G_e + G_s\right)}{\left(\frac{G_i}{n} + G_e + G_s + G_b\right)} + \theta \text{ ambient} \qquad (34)$$

The numerical factor k_{1a} depends upon the type of armouring.

(i) For wire/strip armour,

$$k_{1a} = \sqrt{1 + \left(\frac{\pi}{LR}\right)^2}$$

where LR = is the lay ratio

(ii) For tape armour

$$k_{1a} = \frac{100}{(100\% \quad \text{gap in the tape})}$$

$$= \frac{100}{(100\% \text{ overlap in the tape})}$$

7.2 FOR NON-MAGNETIC ARMOUR

In case of non-magnetic armour as there will be no hysteresis loss in the armour, the general procedure is to combine the armour resistance R_a in parallel with the sheath resistance R_s to determine the eddy current losses. The formulae given in clause 6 are used with the equivalent parallel resistance in place of single sheath resistance R_s and the root mean square value of the sheath and armour diameter in place of mean sheath diameter d_s. This procedure is applicable for all types of cables.

7.3 FOR MAGNETIC ARMOUR

7.3.1 Three Core Cables with Steel Wire/Strip Armour

In three core power cables the armour losses are considerably low compared to single core cables. The value of relative permeability μ_r recommended for steel wire/strip armour is 300, whereas for steel tape it is 3000-5000, considering a constant value of μ_r. This is the reason that hysteresis loss in case of three core, steel wire strip armour may be neglected. Thus $\lambda_2 = \lambda_2''$.

7.3.1.1 Sector shaped conductor cables

$$\lambda_2 = 0.358 \frac{R_a}{R_{ac}} \left(\frac{2r_1}{d_a}\right)^2 \frac{1}{1 + \left(\frac{2.77\ R_a 10^3}{\omega}\right)^2} \qquad (35)$$

where d_a = mean diameter of armour mm

7.3.1.2 Circular conductor cables

a. Common lead sheath

$$\lambda_2 = 1.23 \frac{R_a}{R_{ac}} \left(\frac{2c}{d_a}\right)^2 \frac{1}{1 + \left(\frac{2.77\ R_a 10^3}{\omega}\right)^2} \qquad (36)$$

b. Separate lead sheath (SL) cables

The screening effect of the sheath currents reduces the armour loss. The formula (36) given above is recommended to be used after multiplying by a factor $(1 - \lambda_1')$ where λ_1' is obtained from sub-clause 6.2.1 formula (18).

7.3.2 Three Core Cables with Steel Tape Armour

In this case both the hysteresis as well as the eddy current losses should be considered. These combined losses computed for

power frequency of 50Hz are given as below

$$\lambda_2 = \lambda_2' + \lambda_2'' = \frac{a^2 k^2 10^{-4}}{R_{ac} d_a \delta} \quad 1 + 0.225\ \delta^2 \tag{37}$$

where k is given by

$$k = \frac{1}{1 + \frac{d_a}{\mu\delta}}$$

For frequency other than 50 Hz the value calculated from (37) must be multiplied by the factor $\left(\frac{f}{50}\right)^2$.

7.3.4 Two Core Cables with Steel Wire/Strip Armour

As explained in Clause 7.3.1 the hysteresis loss in this case can be neglected. The eddy current loss is given as following:

$$\lambda_2 = \lambda_2'' = \frac{0.62\omega^2 10^{-8}}{R_{ac} R_a} + \frac{3.82\ A_a \omega\ 10^{-2}}{R_{ac}} \left[\frac{1.48 r_1 + 2t_i}{d_a^2 + 95.7\ A_a} \right] \tag{38}$$

CHAPTER 8

THERMAL RESISTANCES WITHIN THE CABLE

Thermal resistance offered to the flow of heat from the conductor(s) to the outer surface of the cable depends upon thermal resistivity of the materials and the geometry of the cable. The thermal resistivity of the cable insulation materials and the particular surrounding materials (filling) are given in Table V. The formulae for the computation of thermal resistances of different parts of the cables under consideration are given as following.

Table V

Thermal Resistivity of Insulation and Protective Covering Materials

S. No.	Material	Thermal Resistivity ρ ($^{\circ}C$ cm/W)
1	Impregnated Paper	550-600
2	PVC	500-650
3	Polyethylene	350-400
4	Crosslinked Polyethylene	350
5	Fibrous bedding materials	600
6	Hessian Outer Serving	600
7	Natural Rubber	500
8	Silicon Rubber	550
9	Butyl Rubber	500
10	Ethylene Propylene Rubber	550
11	Nitrite Butyl Rubber	500
12	Poly Chloroprene Rubber	550
13	Glass Fiber Braid	600

8.1 THERMAL RESISTANCE OF INSULATION (DIELECTRIC) G_i

8.1.1 Single Core and SL Type Cables:

$$G_i = \frac{\rho_i}{2\pi} \ln \left(1 + \frac{2t_i}{d_c}\right) \ ^\circ C \ cm/W \qquad (39)$$

where

ρ_i Thermal resistivity of insulating material in $^\circ C$ cm/W

t_i Thickness of insulation in mm

Note: In this entire routine 8, the thickness of extruded semiconductive layer, if any, should be included with t_i instead with d_c.

8.1.2.1 Circular conductor belted cables

$$G_i = \frac{\rho_i}{2\pi} G_1 \quad ^\circ C \ cm/W \qquad (40)$$

where

G_1 is geometric factor which is a function of the M_{ie} formula M and the simon correction factor G_{s1}.

$G_1 = MG_{s1}$

The geometric factor G_1 for multicore belted cables is given by simon. It is a function of two independent variables. These variables for entry into each of the computer routines are X and Y where

$$X = \frac{t_i + t_b}{d_c} \quad \text{and} \quad Y = \frac{t_b}{t_i}$$

and the value of G_1 is obtained on exit from each routine.

The M_{ie} formula for two, three and four core cables is as given

$$M = \ln \frac{1 - \alpha\beta + (1-\alpha^2)(1-\beta^2)^{1/2}}{\alpha-\beta} \qquad (41)$$

where α and β are given as following for two core cables

$$\alpha = \frac{1}{\left[1 + \dfrac{X}{1 + \dfrac{X}{1+Y}}\right]^2}$$

$$\beta = \alpha = \frac{\frac{X}{1+Y} - \frac{1}{2}}{\frac{X}{1+Y} - \frac{3}{2}}$$

For three core cables

$$\alpha = \frac{1}{\left[1 + \frac{2x}{1 + \frac{2}{\sqrt{3}}\left(1 + \frac{2X}{1+Y}\right.}\right]^3}$$

$$\beta = \alpha = \frac{\frac{2}{\sqrt{3}}\left(1 + \frac{2X}{1+Y}\right) - 3}{\frac{2}{\sqrt{3}}\left(1 + \frac{2X}{1+Y}\right) + 3}$$

For four core cables

$$\alpha = \frac{1}{\left[1 + \frac{X}{\frac{1}{2} + \frac{1}{\sqrt{3}} + \frac{\sqrt{2}X}{1+Y}}\right]^4}$$

$$\beta = \alpha = \frac{\frac{X}{1+Y} - \left(2 - \frac{1}{2}\right)}{\frac{X}{1+Y} + \left(\sqrt{2} + \frac{1}{2}\right)}$$

The Simon correction factor G_{sl} is a function of two independent variables X and Y as defined above, denoted by G_{sl} (X,Y). For the computation of G_{sl} (X,Y), the quadratic interpolation method is suggested.

For two core cables

$G_{sl}(X,0) = 1.06019 - 0.0671778X + 0.0179521X^2$

$G_{sl}(X,0.5) = 1.06798 - 0.0651648X + 0.015825X^2$

$G_{sl}(X,1) = 1.06700 - 0.0557156X + 0.0123212X^2$

For three core cables

$G_{sl}(X,0) = 1.11083 - 0.0996778X + 0.0229169X^2$

$G_{sl}(X,0.5) = 1.10713 - 0.0750019X + 0.0139655X^2$

$G_{sl}(X,1) = 1.09831 - 0.0720631X + 0.0145909X^2$

For four core cables

$$G_{s1}(X,0) = 1.11083 - 0.0996778X + 0.0229169X^2$$

$$G_{s1}(X,0.5) = 1.10713 - 0.0750019X + 0.0139655X^2$$

$$G_{s1}(X,1) = 1.10284 - 0.0620597X + 0.0107582X^2$$

The values of $G_{s1}(X,Y)$ may be obtained by quadratic interpolation using the following formula:

$$G_{s1}(X,Y) = G_{s1}(X,0) + Y\left[-3G_{s1}(X,0) + 4G_{s1}(X,0.5) - G_{s1}(X,1)\right]$$
$$Y^2 \left[2G_{s1}(X,0) - 4G_{s1}(X,0.5) + 2G_{s1}(X,1)\right]$$

8.1.2.2 For circular conductor screened cables

The value computed by formula (40), given in sub-clause 8.1.2.1 is multiplied by the screen correction factor S_2; hence,

$$G_i = \frac{\rho_i}{2\pi} G_1 S_2 \ {}^\circ\text{C cm/W} \qquad (41)$$

The formula used in the computer routines for computation of S_2 has been obtained by curve fitting applied to graphical values. S_2 is a function of two independent variables X_1 and Y_1 given as below:

$$X_1 = \frac{t_{sc}\ \rho_i}{d_c\ \rho_{sc}}$$

$$Y_1 = \frac{t_i + t_b}{d_c}$$

where

t_{sc} Thickness of metallic screen/concentric conductor mm

ρ_{sc} Thermal resistivity of metallic screen/concentric conductor material in °C cm/W (Table V)

The value of $S_2(X_1,Y_1)$ is obtained again by quadratic interpolar for $0 < X_1 \leq 6$

$$S_2(X_1,0.2) = 0.998095 - 0.123369X_1 + 0.0202620X_1^2 - 0.00141667X_1^3$$

$$S_2(X_1,0.6) = 0.999452 - 0.0896589X_1 + 0.0120239X_1^2 - 0.000722228X_1^3$$

$S_2(X_1,1) = 0.997976 - 0.0528571X_1 + 0.00345238X_1^2$

for $0 < X_1 \leq 25$

$S_2(X_1,0.2) = 0.824160 - 0.0288721X_1 + 0.000928511X_1^2 - 0.0000137121X_1^3$

$S_2(X_1,0.6) = 0.853348 - 0.0246874X_1 + 0.000966967X_1^2 - 0.0000159967X_1^3$

$S_2(X_1,1) = 0.883287 - 0.0153782X_1 + 0.000260292X_1^2$

The value of $S_2(X_1,Y_1) = S_2(X_1,0.2) + Z_1[-3S_2(X_1,0.2)+4S_2(X_1,0.6)-S_2(X_1,1.0)] + Z_1^2[2S_2(X_1,0.2) - 4S_2(X_1,0.6) + 2S_2(X_1, 1.0)]$

Where $Z_1 = 1.25Y_1 - 0.25$

8.1.2.3 Shaped conductor belted cables

In this case the value of G_i computed by formula (40) given in sub-clause 8.1.2.1 is multiplied by the Sector Correction Factor S_1. Thus the formula for G_i is :

$$G_i = \frac{\rho_i}{2\pi} G_1 S_1 \ {}^{\circ}\mathrm{cm/W} \tag{42}$$

where S_1 = Sector Correction Factor

S_1 is a function of two independent variables, X_2 and Y_2 given below. It is suggested to be computed with the help of linear interpolation.

$$X_2 = \frac{t_i + t_b}{d_c}$$

$$Y_2 = \frac{t_i + t_b}{2t_i}$$

where d_c in case of sector shaped conductor is the equivalent diameter of the circular conductor after taking into account the effect of lay and in case of oval conductors

$d_c = \sqrt{\text{Major axis X Minor axis}}$

for two core cables

$X_2 \leq 0.4$

$S_1(X_2,0.5) = 0.364725 + 2.17407X_2 - 4.70957X_2^2 + 3.94748X_2^3$

$S_1(X_2,1.0) = 0.349795 + 2.56709X_2 - 6.34630X_2^2 + 6.33862X_2^3$

$0.4 < X_2 \leq 1.6$

$S_1(X_2,0.5) = 0.587061 + 0.467744X_2 - 0.278245X_2^2 + 0.0585659X_2^3$

$S_1(X_2,1.0) = 0.600138 + 0.545511X_2 - 0.362536X_2^2 + 0.0856639X_2^3$

for three core cables

$X_2 \leq 0.4$

$S_1(X_2,0.5) = 0.384333 + 2.24410X_2 - 5.25992X_2^2 + 4.90519X_2^3$

$S_1(X_2,1.0) = 0.390339 + 2.42938X_2 - 6.30983X_2^2 + 6.59533X_2^3$

$0.4 < X_2 \leq 1.6$

$S_1(X_2,0.5) = 0.585762 + 0.550242X_2 - 0.359514X_2^2 + 0.0830415X_2^3$

$S_1(X_2,1.0) = 0.626273 + 0.466385X_2 - 0.268880X_2^2 + 0.0571091X_2^3$

for four core cables

$X_2 \leq 0.4$

$S_1(X_2,0.5) = 0.461412 + 1.83393X_2 - 4.26606X_2^2 + 4.18568X_2^3$

$S_1(X_2,1.0) = 0.450545 + 2.04024X_2 - 4.93175X_2^2 + 4.89309X_2^3$

$0.4 < X_2 \leq 1.6$

$S_1(X_2,0.5) = 0.642645 + 0.424146X_2 - 0.215233X_2^2 + 0.0372956X_2^3$

$S_1(X_2,1.0) = 0.665106 + 0.368835X_2 - 0.151572X_2^2 + 0.0154424X_2^3$

The value of $S_1(X_2, Y_2) = S_1(X_2,0.5) + 2.0(y_2 - 0.5)$

$(S_1(X_2,1.0) - S_1(X_2,0.5))$

8.1.2.4 For shaped conductor screened cables

The value of G_i computed by formula (42) in sub-clause 8.1.2.3 is multiplied by the screen correction factor S_2' for shaped conductors:

$$G_1 = \frac{\rho_i}{2\pi} G_1 S_1 S_2' \ ^\circ C \ cm/W \qquad (43)$$

The screen correction factor S_2' is a function of two independent variables X_1 and Y_1 described in sub-clause 8.1.2.1 and dc the equivalent diameter.

$0 < X_1 \leq 3$

$S_2'(X_1,0.2) = 1.00169 - 0.0945X_1 + 0.00752381X_1^2$

$S_2'(X_1,0.6) = 1.00171 - 0.0769286X_1 + 0.005371X_1^2$

$S_2'(X_1,1.0) = S_2(X_1,0.6)$

$3 \leq X_1 \leq 1.6$ $\quad S_2'(X_1,0.2) = S_2'(X_1,0.6)$ are given by the same formulae as for $0<X_1\leq 3$.

$S_2'(X_1,1.0) = 1.00117 - 0.0752143X_1 + 0.0053334X_1^2$

$6 < X_1 \leq 25$

$S_2'(X_1,0.2) = 0.81164 - 0.0238413X_1 + 0.000994933X_1^2 + 0.0000155152X$

$S_2'(X_1,0.6) = 0.833598 - 0.0223155X_1 + 0.000978956X_1^2 + 0.00001583111$

$S_2'(X_1,1.0) = 0.842875 - 0.0227255X_1 + 0.00105825X_1^2 + 0.0000177427X$

The value of $S_2'(X_1,Y_1)$ is once again calculated in the same way as given in the end of sub clause 8.1.2.2.

8.2 THERMAL RESISTANCE OF BEDDING (INNER SHEATHING) G_b

Thermal resistance of beeding (inner sheathing) depends upon whether cable is having a common metal sheath or separate sheaths/concentric conductors/screen.

8.2.1 Single Core Cables or Multicore Cables with Common Metal Sheath:

$$G_b = \frac{\rho_b}{2\pi} \ln \left[1 + \frac{2t_b}{d_b}\right] \ ^\circ C \ cm/W \qquad (45)$$

Where

t'_b Bedding (inner sheathing) thickness in mm

d_b Diameter below bedding (inner sheathing)

Note : The above formula is valid for all the cases where a cylindrical surface is available below the bedding/inner sheathing.

8.2.2 Separately metal sheath (SL) / concentric conductor / Screened, circular conductor cables

In this case thermal resistance of filling/warming material has to be computed along with the thermal resistance of bedding/inner sheathing. This will depend upon whether sheaths/concentric conductors are touching or sheaths are having equal thickness of bedding material between sheaths and between sheath and armour.

$$G_b = \frac{\rho_b}{6\pi} \bar{G}_1 \ ^{\circ}C\ cm/W \qquad (46)$$

where $\bar{G}_1$ = geometric factor to take into account.

Thermal resistance of filling material sheaths/concentric conductors/screens are touching.

$0 < X_3 \leq 0.03$ $\bar{G}_1 = 2\pi(0.00022619 + 2.11429X_3 - 20.4762X_3^2)$

$0.03 < X_3 \leq 0.15$ $\bar{G}_1 = 2\pi(0.0142108 + 1.17533X_3 - 4.49737X_3^2 + 10.6352X$

where $X_3 = \frac{t_b}{d_b}$

When sheaths are having equivalent thickness of bedding between sheaths and between sheaths and armour

for $0 < X_3 \leq 0.03$ $\bar{G}_1 = 2\pi(0.000202380 + 2.03214X_3 - 21.6667X_3^2)$

and for

$0.03 < X_3 \leq 0.15$ $\bar{G}_1 = 2\pi(0.0126529 + 1.101X_3 - 4.56104X_3^2 + 11.5093X_3^3)$

8.3 THERMAL RESISTANCE OF SERVING (OUTER SHEATHING) G_s

Since the serving / outer sheathings are generally in the form of concentric layer(s), the thermal resistance is given by:

$$G_s = \frac{\rho_{bs}}{6\pi} \ln \left(1 + \frac{2t_s}{d_{bs}}\right) \ {}^{\circ}C\ cm/W \tag{47}$$

where

ρ_{as} Thermal resistance of serving/outer sheathing material ($^{\circ}C$ cm/W)

t_s Thickness of serving / outer sheathing (mm)

d_{bs} Diameter below serving/outer sheathing (mm)

CHAPTER 9

EXTERNAL THERMAL RESISTANCE (THERMAL RESISTANCE OF SURROUNDINGS OUT - S9DE THE CABLE) G_e

The common practice in India is either to lay the cable in air or to bury in the ground. Cables are also laid in covered or uncovered trenches/troughs, such cases can be dealt either as cables laid in ground or air depending upon whether the trough is filled or not. Effect of solar radiation on cables laid in open air should also be taken into consideration.

9.1 CABLES LAID IN GROUND (BURIED IN GROUND)

9.1.1 Single Isolated Buried Cable

$$G_e = \frac{\rho_e}{2\pi} \ln \left(U + \sqrt{(U^2-1)}\right) \quad {}^\circ C\ cm/W \tag{48}$$

where

ρ_e = thermal resistivity of solid $^\circ C$ cm/W
(Although it varies from place to place, usual practice is to consider it as 150°C cm/W)

$U = \frac{2L}{D_e}$

L = distance from cable axis to the surface of the ground in mm

D_e = external diameter of the cable in mm

9.1.2 Equally Loaded Identical Cables

(a) Two cables touching each other in flat formation

$$G_e = \frac{\rho_e}{2\pi} \left[\ln (2U) - 0.451\right] \quad {}^\circ C\ cm/W \tag{49}$$

(b) Two cables spaced apart

$$G_e = \frac{\rho_e}{2\pi} \ln \left\{U + \sqrt{(U^2-1)}\right\} + \frac{1}{2} \ln \left\{1 + \frac{2L}{a_1}\right\} \quad {}^\circ C\ cm/W \tag{50}$$

where a_1 = axial distance between cables in mm

(c) Three cables in flat formation touching each other

$$G_e = \rho_e \left\{0.475 \ln \ (2U) - 0.346\right\} \ {}^{\circ}C \ cm/W \qquad (51)$$

(d) Three cables in flat formation equally spaced apart in horizontal plane. (For the cable having maximum sheaths loss i.e. outer cable with lagging phase).

$$G_e = \frac{\rho_e}{2\pi} \left\{\ln \left\{U + \sqrt{(U^2-1)}\right\} + \ln \left[1 + \left(\frac{2.0 \ L}{s_1}\right)^2\right]\right\} \ {}^{\circ}C \ cm/W \qquad (52)$$

(d) Three cables in trefoil and touching formation with metallic sheathed.

$$G_e = \frac{1.5\rho_e}{\pi} \ln \left\{(2U) - 0.630\right\} \ {}^{\circ}C \ cm/W \qquad (53)$$

with metallic sheathed cables

$$G_e = \frac{\rho_e}{2\pi} \ln \left\{(2U) + 2 \ln \ (u)\right\} \ {}^{\circ}C \ cm/W \qquad (54)$$

Note : L is measured from the centre of trefoil group and D_e is external diameter of any one cable.

(e) Cables buried in troughs/trenches:

Under this condition, there is always a danger of sand becoming dry. Thus G_e can be computed with the help of any formula given above from 47 to 54 (whichever is applicable) except that ρ_e is taken as 250°C cm/W in place of 150°C cm/W.

(f) Group of cables

When group of equally loaded identical cables are placed together, the thermal resistance taken for current rating purposes is that of the hottest cable in that group. It is usually possible to decide from the configuration of the installation which cable will be hottest, but in case of difficulty a further calculation for another cable may be

necessary.

The method is to compute modified value of G_e which takes into account mutual heating of the group, the temperature rise from all cables except the hottest cable of the group being taken as that due to line sources at the cable centres and together with that due to line sources of equal magnitude but opposite sign, located at the mirror images of the cable centres with respect to the solid surface.

The external thermal resistance for the hottest cable "p" of a group of q cables is given by

$$G_e = \frac{\rho_e}{2\pi}\left\{\ln\left(U+\sqrt{(U^2-1)}\right)\left[\frac{dp_1'}{dp_1}\cdot\frac{dp_2'}{dp_2}\cdots\frac{dp_k'}{dp_k}\cdots\frac{dp_q'}{dp_q}\right]\right\}\ {}^{\circ}\mathrm{C\ cm/W} \qquad (56)$$

Where

dp'_k = distance between axis of cable under consideration and axis of the reflex image of kth cable in mm

dp_k = distance between axis of cable under consideration and axis of the kth cable in mm.

9.2 CABLES LAID IN AIR G_e

Thermal resistance of surrounding air depends upon whether the cable is exposed to direct sun or it is protected from the direct solar radiation.

9.2.1 Cables Protected from Direct Solar Radiation

Thermal resistance of surrounding air is given by

$$G_e = \frac{1\times 10^{-2}}{\pi D_e^* h\left(\Delta\theta_{sa}\right)^{1/4}}\ {}^{\circ}\mathrm{C\ cm/W} \qquad (57)$$

where $h = \dfrac{Z}{\left(D_e^*\right)^g} + B$

$D_e^* = D_e \times 10^{-3}$

Z, g and B are constants depending upon the mode of laying, and are given in table No. VI

h = Heat dissipation coefficient W/m^2

$\Delta\theta_{sa}$ = cable surface temperature above ambient temperature. It is calculated as following

$$K_A = \frac{\pi D_e^* h}{\left(1+\lambda_1+\lambda_2\right)} \left[\frac{G_i}{n} + G_b\left(1+\lambda_1\right) + G_s \left(1+\lambda_1+\lambda_2\right)\right]$$

$$\left(\Delta\theta_{sa}\right)_{n+1}^{1/4} = \left[\frac{\Delta\theta_c + \phi d}{1+K_A\left(\Delta\theta_{sa}\right)_n^{1/4}}\right]^{1/4}$$

where ϕ_d is surface temperature rise due to dielectric loss alone.

$$\phi_d = W_d\left[\left(\frac{1}{\left(1+\lambda_1+\lambda_2\right)} - \frac{1}{2}\right) G_i - \frac{n\lambda_2 G_b}{\left(1+\lambda_1+\lambda_2\right)}\right]$$

Thus when dielectric losses are neglected ϕ_d = 0. The above equation can be solved with iterative method by giving initial value of $\left(\Delta\theta_{sa}\right)_n^{1/4} = 2$, till $\left(\Delta\theta_{sa}\right)_{n+1}^{1/4} - \left(\Delta\theta_{sa}\right)_n^{1/4}$ becomes $\leq$ 0.001.

9.2.2 Cables Directly exposed to Solar Radiation

In this case the heat received by cable from solar radiation further limits the permissible temperature rise of conductor above ambient. Thus the revised formula for current rating should be as following:

$$I = \sqrt{\left[\frac{\Delta\theta_c - Wd\left(0.5G_i + n\ (G_b + G_s + G_e^*)\right) - k_o'}{nR_{ac}\left(\frac{G_i}{n} + G_b\left(1+\lambda_1\right) + \left(G_s + G_e^*\right)\left(1 + \lambda_1 + \lambda_2\right)\right)}\right]} \qquad (58)$$

where

k_a' = Temperature rise of conductor because of heat absorbed by the cable surface from solar radiation.

k_a = $\sigma\ D_e^*\ H\ G_e^*\ 10^{-2}$

σ = absorption coefficient of solar radiation for the cable surface, the usual recommended values are:

Bitumen/Jute serving	-0.8
Polychloroprene	-0.8
PVC	-0.6
Polethylene	-0.4
Lead	-0.6

H = Intensity of solar radiation. It varies with latitude of the place, but in the absence of local value of H, it can be taken as $10^3 W/m^2$.

G_e^* = External thermal resistance of free air, adjusted to take into account the solar radiation.

$$G_e^* = \frac{1}{\pi D_e^* \; h \; \left(\Delta\theta_{s'a}\right)^{1/4}} \; {}^\circ C \; cm/W \qquad (59)$$

$\Delta\theta_{sa}'$ = cable surface temperature above ambient temperature after absorbing solar radiation.

$\left(\Delta\theta_{s'a}\right)_{n+1}^{1/4}$ can be calculated as following

$$\left(\Delta\theta_{s'a}\right)_{n+1}^{1/4} = \left[\frac{\Delta\theta_c + \phi_d + \phi_s}{1 + K_A + \left(\Delta\theta_{s'a}\right)_n^{1/4}}\right]^{1/4}$$

The above equation can be solved with iterative method by giving initial value of $\left(\Delta\theta_{s'a}\right)_{n+1}^{1/4} = 2$ till $\left(\Delta\theta_{s'a}\right)_{n+1}^{1/4} - \left(\Delta\theta_{s'a}\right)_n^{1/4}$ becomes ≤ 0.001.

where

ϕ_s = a factor by which cable surface temperature is raised because of solar radiation

$$\phi_s = \frac{\sigma D_e^* H}{(1+ \lambda_1 + \lambda_2)} \left[\frac{G_i}{n} + G_b \left(1 + \lambda_1\right) + G_s\left(1 + \lambda_1 + \lambda_2\right)\right]$$

ϕ_d = a factor by which cable surface temperature is raised because of dielectric losses.

Note : If dielectric losses are negligible then ϕ_d and W_d become zero and these should be neglected from the formula given above.

TABLE VI

Values for constants Z, B and g for black surfaces of cables in free air

(A) In free air, installed on non-continuous brackets, ladder supports or cleats, D_e not greater than 0.15 m.

No.	Installation	Z	b	G	Mode
1	Single cable +	0.21	3.94	0.60	≥0.3De
2	Two cables touching, horizontal	0.29	2.35	0,50	≥0.5De
3	Three cables in trefoil	0.96	1.25	0.20	≥0.5De
4	Three cables touching, horizontal	0.62	1.95	0.25	≥0.5De
5	Two cables touching vertical	1.42	0.86	0.25	≥0.5De
6	Two cables, spaced D_e, vertical	0.75	2.80	0.30	≥0.5De
7	Three cables touching, vertical	1.61	0.42	0.20	≥0.1De
8	Three cables, spaced D_e, vertical	1.31	2.00	0.20	≥0.5De

(b) Clipped directly to a vertical wall (D_e not greater than 0.08 m)

9.	Single cable	1.60	0.63	0.25	
10.	Three cables in trefoil	0.94	0.79	0.20	

\+ Values for a "single cable" also apply to each cable of a group when they are spaced horizontally with a clearance between cables of at least 0.75 times the cable overall diameter.

9.3 CABLE LAID IN DUCTS/PIPES

The thermal resistance of surrounding medium when cables are laid in ducts consists of three parts:

1. the thermal resistance of air space between the cable surface and duct internal surface G'_s
2. the thermal resistance of duct or pipe itself (if the pipe is metallic it can be neglected) G''_e
3. the external thermal resistance surrounding the duct G'''_e

G_e = total external thermal resistance for the cable

$$G_e = G'_e + G''_e + G'''_e$$

Note : If the ducts are completely filled with pumpable material having thermal resistivity not exceeding that of the surrounding soil, or if the ducts are sealed to preserve the moisture contents of the filling material, the system may be located as directly buried cables.

$$G'_e = \frac{p'}{1 + 0.1\ (q' + \theta m')\ D_e}$$

p′, q′, and r′ are given in table VII.

θm = the mean temperature of the medium filling the space between cable and duct. An assumed value has to be used initially and the calculations repeated with a modified value later on (if necessary).

$$G''_e = \frac{\rho_{ed}}{2\pi} \ln \left(\frac{D_o}{D_d}\right)$$

where

ρ_{ed} = thermal resistance of duct material °C cm/W (for metal pipes

it can be taken as zero for non metals values are given in Table V)

D_o = the outside diameter of duct in mm

D_d = the inside diameter of duct in mm

G_e'' = If duct are buried in ground then this can be calculated in the same way as G_e calculated in clause 9.1, except that the external diameter of cable is replaced by external diameter of the duct.

If ducts are embedded in concrete, the calculation of thermal resistance is first done with thermal resistivity of concrete as 100°C cm/W, assuming uniform medium. Later on, a correction is added algebraically to take account of the difference, if any, between the thermal resistivity of concrete and surrounding soil for that part of the thermal circuit.

The correction to the thermal resistance is given by:

$$\frac{N_1}{2\pi}\left(\rho_e\right) \ln\left(u_1 + \sqrt{(u_1^2 - 1)}\right) \ °C\ cm/W$$

where

N_1 = Number of loaded cables in the duct

$u_1 = \frac{L_g}{r_b}$

L_g = depth of laying of centre of duct bank in mm

r_b = equivalent radius of concrete bank in mm

$r_b = e^{Y'}$

$$Y' = \frac{X_d}{2Y_d}\left(\frac{4}{\pi} - \frac{X_d}{Y_d}\right) \ln\left(1 + \frac{Y_d^2}{Xd^2}\right) + \ln\left(\frac{X_d}{2}\right)$$

X_d = shorter side of duct bank section in mm

Y_d = longer side of duct bank section in mm

Table VII

Values of Constants p', q' and r'

Installation Condition	p'	q'	r'
In metallic conduit	5.2	1.4	0.011
In fibre duct in air	5.2	0.83	0.006
In fibre duct in concrete	5.2	0.91	0.010
In asbestos cement duct in air	5.2	1.2	0.006
In asbestos cement duct in concrete	5.2	1.1	0.011
Gas pressure cable in pipe	0.95	0.46	0.0021
Oil pressure pipe type cable	0.26	0.0	0.0026
Earthenware ducts	1.87	0.28	0.0036

CONCLUSION

The development of algorithm for the computation of continuous current rating of power cables (for different possible combinations of circumstances) has been done in 8 different parts to make it less complex and understandable. These parts then have been integrated into the main program. The program was successfully tested for different types of cables. With the growing diversity in demand on the part of cable users, it has become rather difficult for the cable manufacturers to cater to them appropriately. Any variation in the installation conditions causes a change in the current carrying capacity, thereby changing the requirements and sometimes even rendering the whole bulk of cable inappropriate. Also, with the advent of new technology, many new types of insulating materials, sheathing materials, serving materials etc have been applied, the use of which can reduce the cost and increase the efficiency considerably. In the absence of any software tool for the computation of the capacity of cables, it had been rather time consuming and tiresome for cable manufacturers to incorporate or even test these changes. The software which has been developed in this work, can thus prove to be of great help to them and herein underlies the practical and commercial importance of this work.

The rating factors for difference in environment, formation, laying etc, have been provided in appendix III and should be appropriately applied to cater for different environments and modes of installation.

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5. Waddicor, The Principles of Electrical Power Transmission, Asian Publishing House, 1961.
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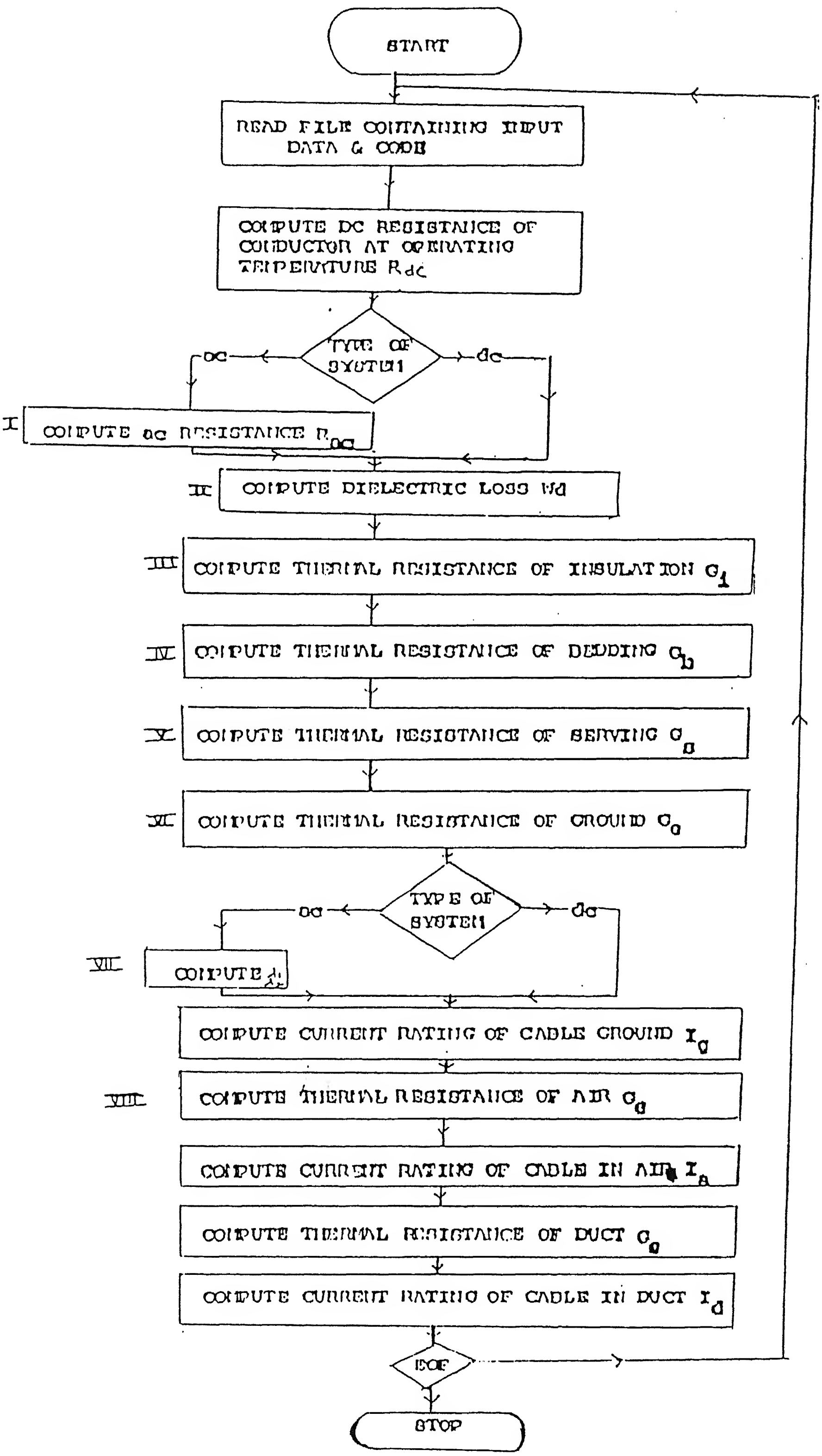
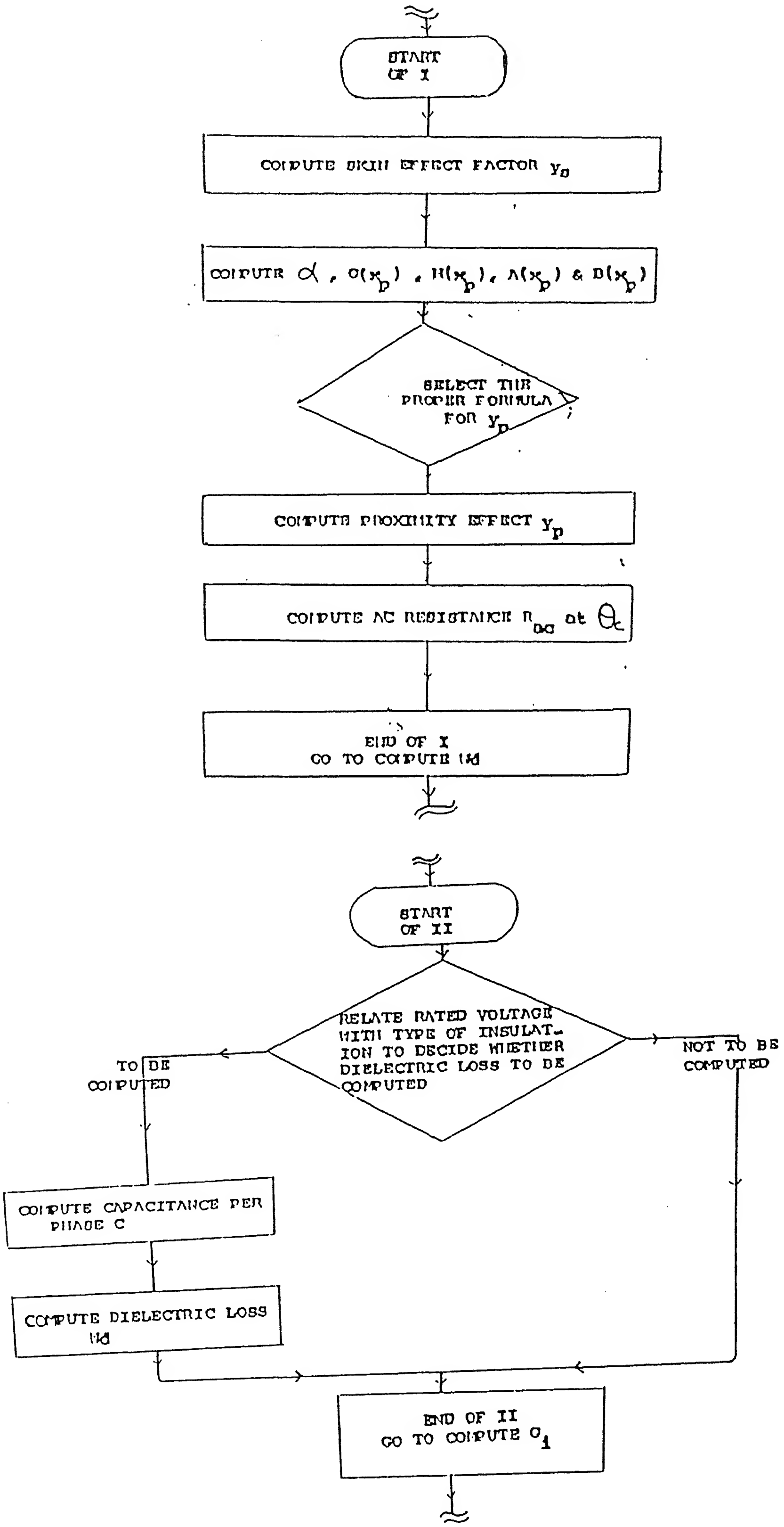
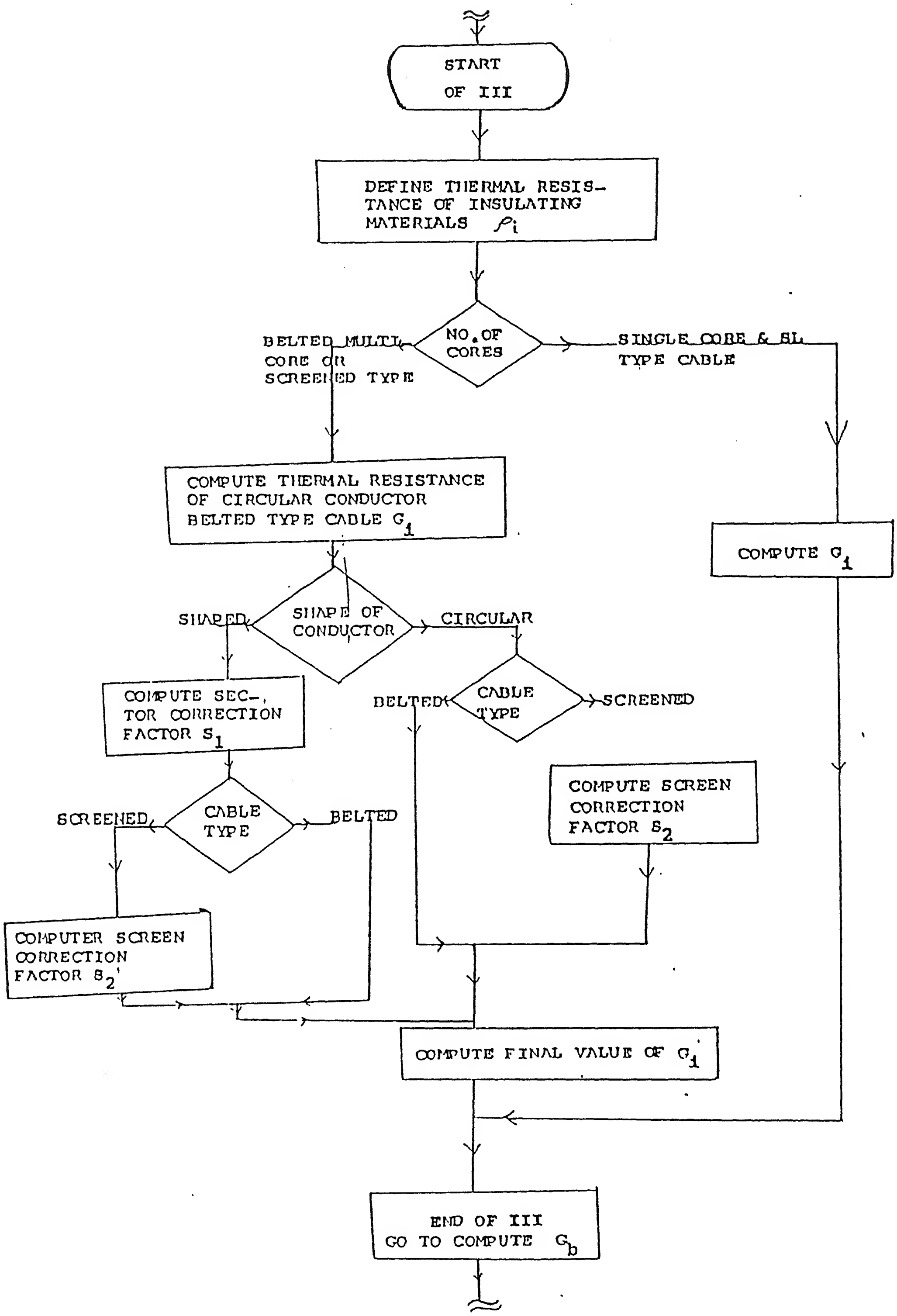
APPENDIX I

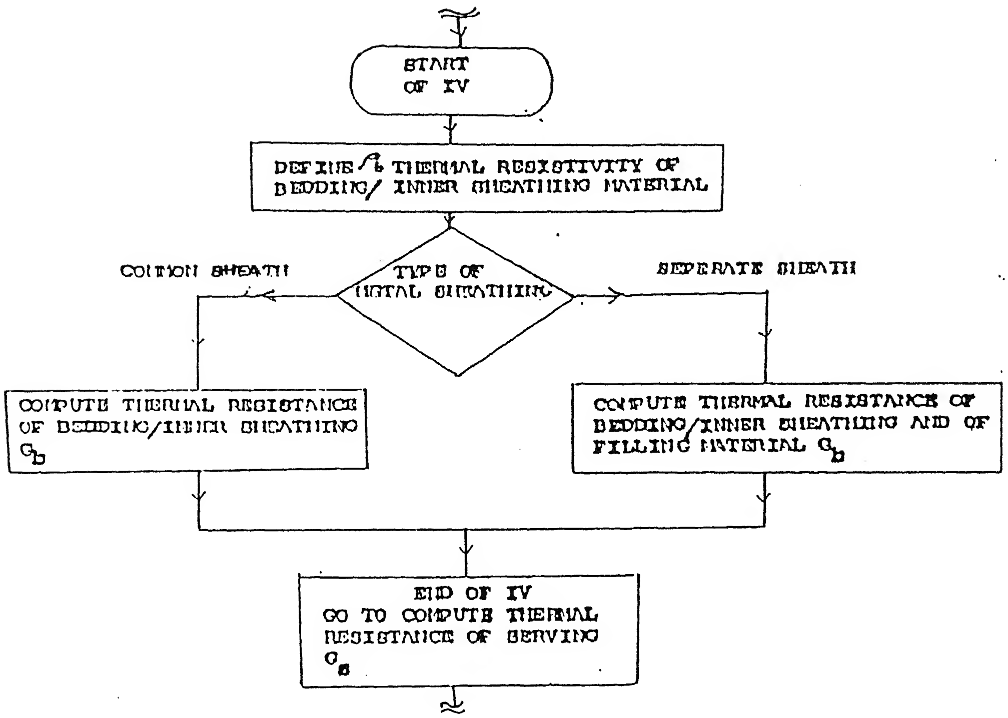
ALGORITHM

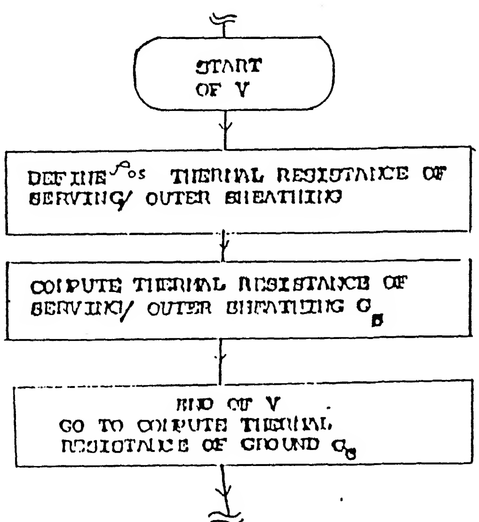
FLOW CHART FOR COMPUTATION OF CONTINUOUS CURRENT CARRYING CAPACITY

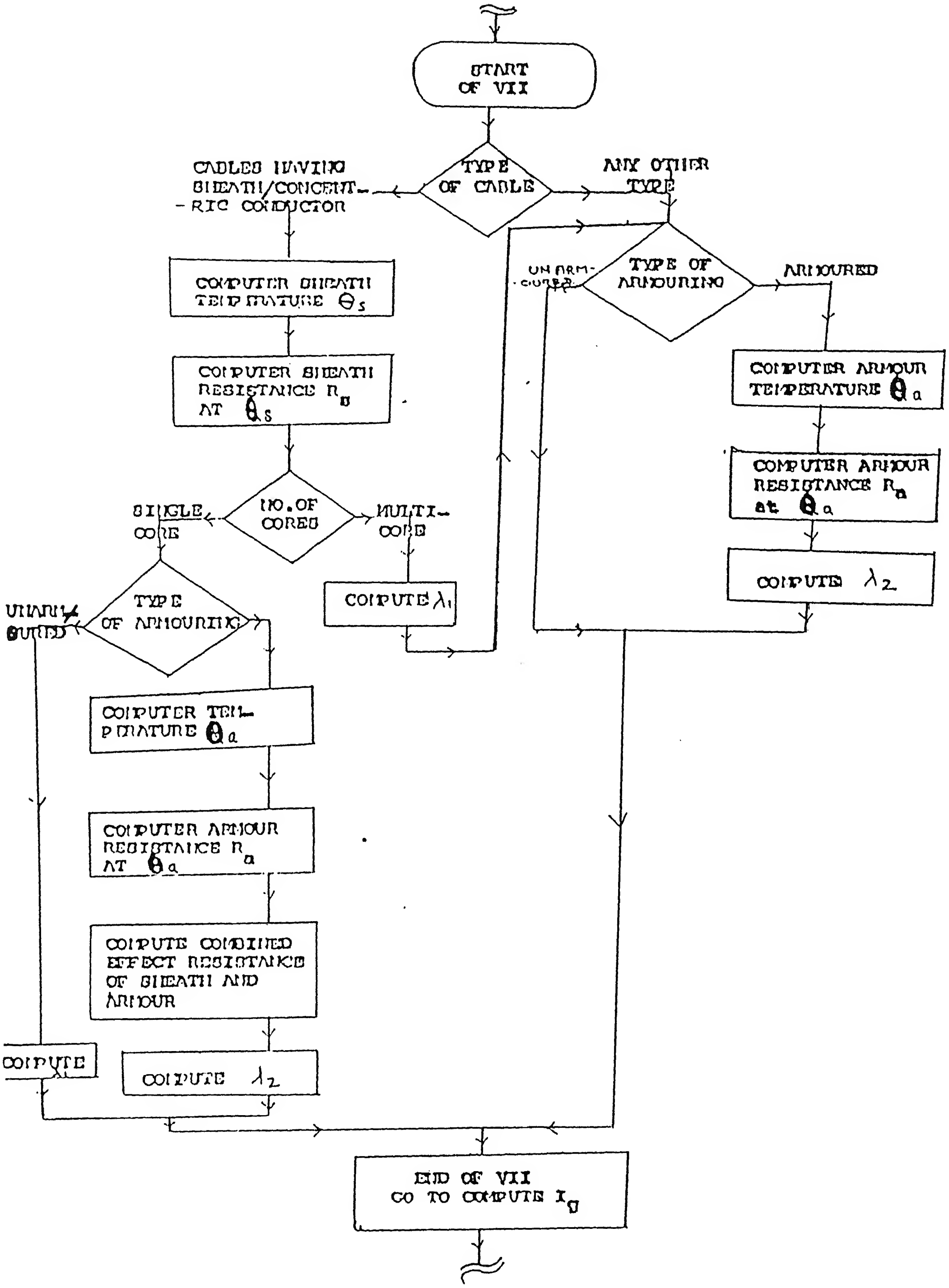



START
OF I
COMPUTE SKIN EFFECT FACTOR y_s
COMPUTE α, $G(x_p)$, $H(x_p)$, $A(x_p)$ & $B(x_p)$
SELECT THE PROPER FORMULA FOR y_p
COMPUTE PROXIMITY EFFECT y_p
COMPUTE AC RESISTANCE R_{ac} at θ_c
END OF I
GO TO COMPUTE Wd
START
OF II
RELATE RATED VOLTAGE WITH TYPE OF INSULATION TO DECIDE WHETHER DIELECTRIC LOSS TO BE COMPUTED
TO BE COMPUTED
NOT TO BE COMPUTED
COMPUTE CAPACITANCE PER PHASE C
COMPUTE DIELECTRIC LOSS Wd
END OF II
GO TO COMPUTE G_1

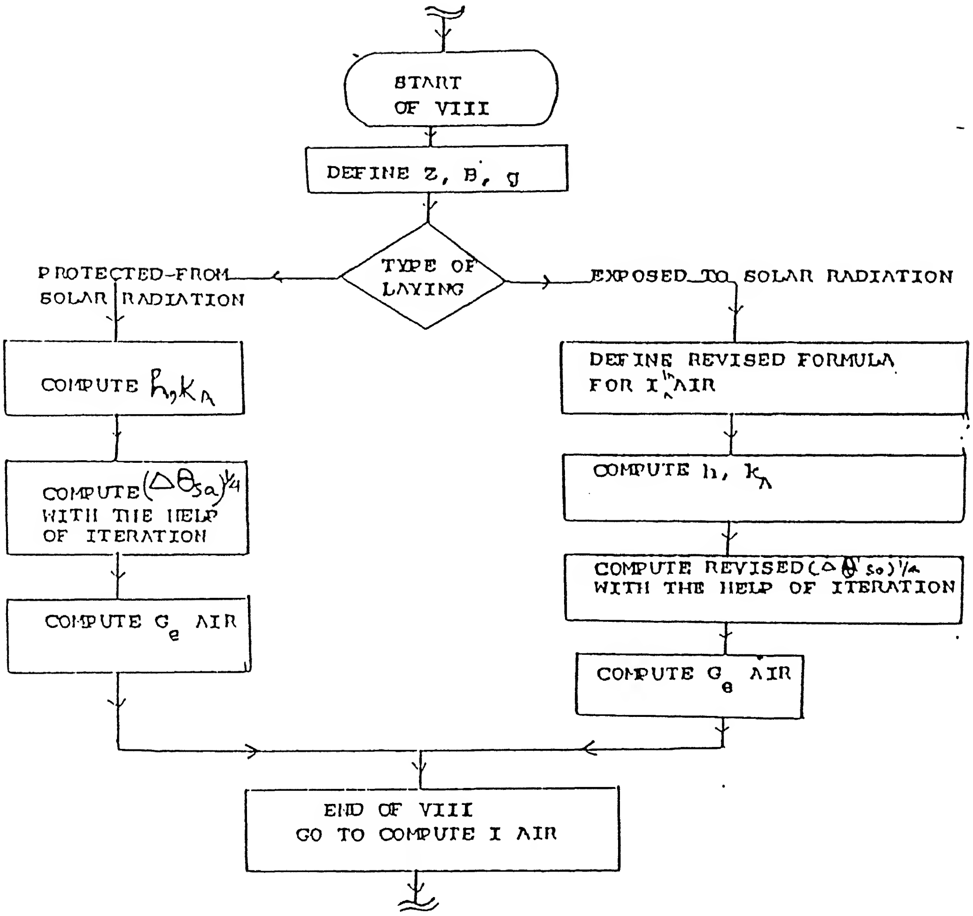

START OF III
DEFINE THERMAL RESISTANCE OF INSULATING MATERIALS ρ_i
NO. OF CORES
BELTED MULTI CORE OR SCREENED TYPE
SINGLE CORE & SL TYPE CABLE
COMPUTE THERMAL RESISTANCE OF CIRCULAR CONDUCTOR BELTED TYPE CABLE G_1
COMPUTE G_1
SHAPE OF CONDUCTOR
SHAPED
CIRCULAR
COMPUTE SECTOR CORRECTION FACTOR S_1
CABLE TYPE
BELTED
SCREENED
COMPUTE SCREEN CORRECTION FACTOR S_2
CABLE TYPE
SCREENED
BELTED
COMPUTER SCREEN CORRECTION FACTOR S_2'
COMPUTE FINAL VALUE OF G_1'
END OF III GO TO COMPUTE G_b

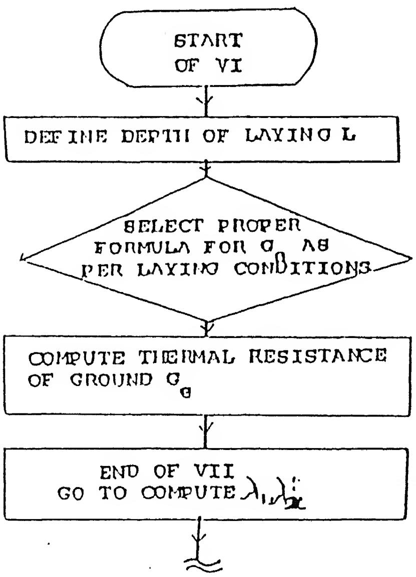

START OF IV
DEFINE ρ_b THERMAL RESISTIVITY OF BEDDING/ INNER SHEATHING MATERIAL
TYPE OF METAL SHEATHING
COMMON SHEATH
SEPERATE SHEATH
COMPUTE THERMAL RESISTANCE OF BEDDING/INNER SHEATHING G_b
COMPUTE THERMAL RESISTANCE OF BEDDING/INNER SHEATHING AND OF FILLING MATERIAL G_b
END OF IV
GO TO COMPUTE THERMAL RESISTANCE OF SERVING G_s


START OF V
DEFINE ρ_{os} THERMAL RESISTANCE OF SERVING/ OUTER SHEATHING
COMPUTE THERMAL RESISTANCE OF SERVING/ OUTER SHEATHING G_s
END OF V
GO TO COMPUTE THERMAL RESISTANCE OF GROUND G



START OF VII
TYPE OF CABLE
CABLES HAVING SHEATH/CONCENTRIC CONDUCTOR
ANY OTHER TYPE
COMPUTER SHEATH TEMPERATURE θ_s
COMPUTER SHEATH RESISTANCE R_s AT θ_s
NO. OF CORES
SINGLE CORE
MULTI-CORE
COMPUTE λ_1
TYPE OF ARMOURING
UNARMOURED
COMPUTER TEMPERATURE θ_a
COMPUTER ARMOUR RESISTANCE R_a AT θ_a
COMPUTE COMBINED EFFECT RESISTANCE OF SHEATH AND ARMOUR
COMPUTE λ_1
COMPUTE λ_2
TYPE OF ARMOURING
UN ARMOURED
ARMOURED
COMPUTER ARMOUR TEMPERATURE θ_a
COMPUTER ARMOUR RESISTANCE R_a at θ_a
COMPUTE λ_2
END OF VII GO TO COMPUTE I_g


START OF VIII
DEFINE Z, B', g
TYPE OF LAYING
PROTECTED-FROM SOLAR RADIATION
EXPOSED TO SOLAR RADIATION
COMPUTE h, K_A
COMPUTE $(\Delta\theta_{sa})^{1/4}$ WITH THE HELP OF ITERATION
COMPUTE G_e AIR
DEFINE REVISED FORMULA FOR I_A^{h} AIR
COMPUTE h, K_A
COMPUTE REVISED $(\Delta\theta'_{sa})^{1/4}$ WITH THE HELP OF ITERATION
COMPUTE G_e AIR
END OF VIII GO TO COMPUTE I AIR


START OF VI
DEFINE DEPTH OF LAYING L
SELECT PROPER FORMULA FOR G_e AS PER LAYING CONDITIONS
COMPUTE THERMAL RESISTANCE OF GROUND G_e
END OF VII GO TO COMPUTE λ_1, λ_{ii}

APPENDIX 2

Rating factors

For Envi ronment and different formations & Laying/Spacing

1. Rating factors for variation in ground temperature

Ground Temperature°C	15	20	30	35	40	45
Rating factor	1.17	1.12	1.06	0.94	0.87	0.79

1. Rating factors for variation in ambient air temperature:

Air temperature °C	25	30	35	40	45
Rating factor	1.25	1.16	1.09	1.00	0.90

1. Rating factors for variation in ground temperature

Voltage	Depth of laying-Cm	75	90	105	120	150	180
	Rating factor	1.00	0.99	0.98	0.97	0.96	0.95
1.1 kv	Above 25 mm& up to 300 mm²	1.00	0.98	0.97	0.96	0.94	0.93
	Above 300 mm²	1.00	0.97	0.96	0.95	0.92	0.91
3 3 kv							
6.6 kv	All sizes		1.0	9.99	8.98	0.96	0.95

1. Group rating factors for circuits of two single core cables, side by side and touching, horizontal formation laid direct in ground

No. of Circuits	Spacing (Between Centre of Circuits) Touching	15 cm	30 cm	45 cm	60 cm
2	0.80	0.85	0.90	0.93	0.95
3	0.70	0.78	0.85	0.88	0.91
4	0.63	0.73	0.81	0.86	0.88
6	0.56	0.67	0.77	0.83	0.87
8	0.51	0.64	0.75	0.82	0.86

1. Group rating factors for circuits of Three single core cables, In trefoil and touching, horizontal formation laid direct in ground

No. of Circuits	Spacing (Between Centre of Circuits) Touching	15 cm	30 cm	45 cm	60 cm
2	0.78	0.81	0.85	0.88	0.89
3	0.68	0.71	0.78	0.81	0.83
4	0.61	0.65	0.72	0.76	0.79
6	0.53	0.58	0.66	0.71	0.76
8	0.48	0.53	0.61	0.68	0.73

1. Group rating factors for Twin and Multicore cables In Horizontal formations laid direct in ground

No. of Circuits	Axial Spacing Touching	15 cm	30 cm	45 cm	60 cm
2	0.79	0.83	0.87	0.90	0.91
3	0.69	0.75	0.79	0.83	0.86
4	0.62	0.69	0.75	0.79	0.82
6	0.55	0.62	0.69	0.75	0.78
8	0.50	0.58	0.66	0.72	0.76

Group rating factors for Twin and multi core cables in TIER. Formation laid direct in ground

No. of Circuits	Axial Spacing				
	Touching	15 cm	30 cm	45 cm	60 cm
2	0.81	0.83	0.88	0.89	0.91
4	0.60	0.67	0.73	0.76	0.78
6	0.51	0.57	0.63	0.67	0.69
8	0.46	0.51	0.56	0.59	0.61

Group rating factors for twin and Multi core cables in Single way stone ware ducts and iron pipes in their formations horizontal formation laid direct in ground

No. of Ducts	Spacing		
	Touching	15 cm	30 cm
4	0.76	0.79	0.81
6	0.67	0.71	0.74
9	0.58	0.61	0.63
12	0.54	0.57	0.60

Group Rating Factors for twin and multi core cables in single way ducts and pipes in Horizontal formation

Spacing	Number of ducts					
	2	4	6	8	10	12
1 to 2 cm	0.88	0.77	0.71	0.67	0.65	0.63

Rating factors for multicore cables laid on racks InAir (with spacing between cables equal to diameter of the cable.)

Number of racks	Number of cable per rack				
	1	2	3	6	9
1	1.0	0.98	0.96	0.93	0.92
2	1.0	0.95	0.93	0.90	0.89
3	1.0	0.94	0.92	0.89	0.88
6	1.0	0.93	0.90	0.87	0.86

Rating factors for multicore cables laid in racks inAir (with cable Touching)

Number of racks	Number of cable per rack				
	1	2	3	6	9
1	1.0	0.84	0.80	0.75	0.73
2	1.0	0.80	0.76	0.71	0.69
3	1.0	0.78	0.74	0.70	0.68
6	1.0	0.76	0.72	0.68	0.66

APPENDIX-III

USER'S GUIDELINES AND AN ILLUSTRATIVE EXAMPLE

A)USER'S GUIDELINES:

The user of this software package should have the following informations before using this package:-

1) Type of system-Whether ac or dc.

2)Frequency of supply (for ac only)

3)Cross sectional area of the conductor-

If it is not a standard one then the value of dc resistance at 20 deg should also be entered.

4)Conductor type-- Round ,segmental or hollow

5)No. of equally loaded conductors.

6)Number of cores

7)Cable type - belted or screened.

If belted then thickness fo belt insulation (including semiconducting layer(if any)is required

If screened then thickness of metallic screen is required.

8)Shape of the conductor --circular or shaped.

If shaped then circumscribing radius of conductors is required.

9)Material of sheath/screen.

10)Whether armoured or unarmoured.

If armoured then following informations are also required-

a)Cross sectional area and mean dia of the armour

b)Type of armour-

Wire/strip armour?- Enter lay ratio.

Tape armour?- Enter percentage overlap or gap.

c)Material of the armour.

11)Whether exposed to solar radiation or not?(for cables in air)

12)Material of insulation-paper,PVC,PE,XLPE etc.

In case of paper insulator Enter the max. permissible temperature.

13)Material of the conductor-Copper or aluminium.

14)Dia. of circular conductor and thickness of insulation between conductors.

15)Resistivity of bedding ,insulation and serving.

16)Operating voltage.

17)Bedding(inner sheathing) thickness and dia. below bedding.

18)Serving(outer sheathing) thickness and dia. below serving.

19)Common metal sheath or separate metal sheath?

20)Sheath thickness

21)Depth of laying (for cables buried in ground)

22)External dia. of cable.

23)External dia of metal sheath

24)Mean dia of metal sheath

25)Axial distance between cables.

26)type of installation e.g. trefoil etc.

27)Type of bonding-e.g cross bonding

28)Whether regular transposition or not.

29)Rating factors ,if any.

B)ILLUSTRATIVE EXAMPLE:

Following is an example of a particular type of cable , the specifications of which are as follows:--(cf Barnes,CC:-pp115)/6/

(Here all linear dimensions are in mm and area in mm square):-

1) Type of system- ac

2)Frequency of supply - 50

3)Cross sectional area of the conductor- 1370

4)Conductor type-- Round

5)No. of equally loaded conductors.- 1

6)Number of cores-1

7)Cable type - screened.

thickness of metallic screen - 0.3

8)Shape of the conductor --circular

9)Material of sheath/screen.-- Lead

10)Whether armoured or unarmoured. -Unarmoured

11)Whether exposed to solar radiation or not?-Exposed

12)Material of insulation-paper

max permissible temperature.- 85